Interagency Array Study Report

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The interagency array study was convened in early 1982 to determine which of the world's large radio reception facilities might be feasibly and beneficially enlisted to help support the Voyager encounters at Uranus (1986) and Neptune (1989), and also to examine the future for such similar events and options as might appear. A similar but more specific study of the Parkes Radio Telescope at Uranus Encounter was just then being completed with a strong positive recommendation, and formed the foundation of the broader study. This report describes the approach, driving considerations, and outcome of the interagency array study. The recommendations of the study team concentrated upon the Voyager Encounters: specifically to develop Parkes for the Uranus Encounter, while pursuing related Advanced Systems development work with the Owens Valley Radio Observatory, and to seek support for the Neptune Encounter from Parkes, the VLA, and the Japanese ISAS 64-meter station.

I. Introduction

The interagency array study formally began in early 1982 as a follow-on to the about-to-be-completed study of the support which could be provided by the Parkes Radio Telescope in Australia to the Voyager spacecraft at Uranus. That study had indicated that a quite significant benefit to the encounter could be obtained by arraying Parkes with the Australian DSN complex, and had displayed a technically feasible method of achieving it. The broader arraying study was charged with determining which other facilities might also be feasibly and beneficially employed for the support of Voyager at Uranus, and with examining the Voyager-Neptune Encounter, and such other future events and options as might appear.

There are three general reasons why the DSN is interested in the concept of interagency arraying. First and foremost is the desire on the part of NASA to increase telecommunications link performance for some very special events such as the encounters of Voyager with Uranus in 1986 and Neptune in 1989. The flight of the ISEE-3 (International Sun-Earth Explorer -3) past the comet Giacobini-Zinner in 1985 is a similar special event, although there are no present plans to support it by interagency arrays. Future missions can also be expected to be candidates for such support if they contain events for which the need for intense or high data-rate support is significantly larger than the average throughout the mission.

The second reason is to provide an opportunity for the U.S. to cooperate in international space exploration with those nations that are interested in joining that activity and have established a large radio reception facility. Participation by their scientists can engender support for exploration in general, thus broadening overall interest in international space exploration.

The third reason is to expand the options for the planning of future missions, to make it feasible to pursue missions which would otherwise be severely limited by the telecommunications link at their climax, and as a consequence be too expensive or impractical to develop.

Figure 1 shows the heliocentric trajectory of the two Voyager spacecraft from their launch in 1977 to their excursion beyond the orbit of Neptune, and it indicates the quite dramatic decrease in signal strength for the encounters at the two other planets relative to that at the Jupiter Encounter. These spacecraft were designed to provide superb coverage of the basic mission to Jupiter and Saturn, but with a trajectory option which could take one spacecraft past Uranus and Neptune many years later. The extended mission to Uranus and Neptune was not approved until after Saturn Encounter. Now work is underway both at the ground stations and with the spacecraft control software to make the data return at the outer planet encounters approach that of these first two encounters. Gains available from modifications to the spacecraft data system software are limited to about 3 dB, which means that a significant part of the 13.5-dB decrease in signal level must be compensated for on the ground. Since both money and time are limited, arraying with large apertures from outside the DSN appears to be the only open avenue.

Most of the world's large radio receiving antennas were at least considered in the early stages of the study, but the span of possible choices was narrowed as the study evolved. Table 1 represents the catalog of apertures which were given early consideration, together with their approximate location, and some of their pertinent characteristics. Figure 2 shows the 1986 configuration of the DSN, together with the most prominent candidate observatories for arraying for support of the Voyager at Uranus. These candidates include the Parkes Radio Telescope, the Bonn 100-meter antenna, the Japanese 64- and 45-meter antennas, and the large NRAO and OVRO antennas in the U.S.A. Arecibo is also shown, not because of Voyager, but because of its potential benefits to the ISEE-3 flyby of comet Giacobini-Zinner. The narrowing of options took place primarily because it was recognized that the resources are limited, both for study and for later accomplishment, and that the greatest benefits would accrue through arraying with the largest and best located of the available apertures. Further, the individual apertures had to be large enough so that a significant increment to the mission science return would be obtained without serious technical difficulties in arraying.

While arraying with non-DSN apertures is expected to provide a significant part of the increased reception capability needed for the Voyager, NASA is also looking for growth of its own internal ground network capabilities in the latter part of the 1980's. Several precepts guided the planning for the growth to the planned 1989 DSN configuration. First, the DSN must have the capability and capacity to adequately support all regular long-term mission operations, such as cruise operations and cruise science data gathering; any regular planetary orbiter science gathering, such as the Venus Radar Mapper, or any frequent repeated planetary satellite encounters such as will occur with the Galileo orbital operations around Jupiter. Second, the DSN by itself must be capable of ensuring at least a limited successful encounter for each planetary flight project under normal conditions. Interagency arraying is as yet untested, both technically and organizationally, and depending totally upon it for a flyby encounter is clearly unwise. Even for the stringent conditions of Voyager at Neptune, the DSN alone should be capable of capturing the needed near-continuous general science data and a part of the imaging return. Normal conditions are assumed, with the

Voyager's on-board tape recorder and image data compression software both operative. To justify their use, the interagency arrays must significantly enhance the support provided to the planetary encounters, or to other selected special events. Figure 3 shows a baseline 1989 DSN configuration that is consistent with these precepts and the most prominent of the candidate observatories for that time. Here, the Very Large Array (VLA) near Socorro, New Mexico, has replaced the NRAO antenna in the American longitude. Arecibo is again shown, in this case for its potential for following the Pioneer 10 out of the Solar System.

In looking at the other potential applications of interagency arraying, certain criteria were identified which could be used to select appropriate missions. First, missions to be enhanced through the participation of the radio astronomy observatories should be unique special events; not routine nor regular usage. This restriction does not necessarily apply, however, in the case of a non-DSN aperture sponsored by another space agency, where mutual benefit arrangements could be established to exchange support of flight projects, and perhaps ultimately lead to regular joint operations. Second, participation of another agency should substantially enhance the mission science return, by increasing data volume or mission reliability, and should also provide suitable benefits to the observatory or the agency sponsor of the non-DSN antennas. Such benefits could take the form of exchange of cross-support for other missions, enhanced capabilities which would be left in place after the arraying event concluded, or perhaps assistance in other scientific endeavors of mutual interest. It could also take the form of direct reimbursement. The catalog of suitable NASA candidate missions which were identified is not large, and whether this is due to the true uniqueness of this opportunity or merely to our myopia will only become clear with time.

The recognized suitable candidate missions are the two far outer planet encounters of the Voyager at Uranus (1986) and Neptune (1989), the encounter of ISEE-3 with Giacobini-Zinner (1985), and a potential future Mariner Mark-II mission, Titan Flyby/Titan Probe (1996). Other candidates are possible, and if, for example, some future spacecraft approached a flyby, or a probe release event or an orbit insertion with a severely degraded telecommunications capability, these events could qualify as suitable for interagency arraying support. Further into the future, exchange of mission support between NASA and other space agencies could become routine for peak load sharing, or for better viewing geometry.

This report provides a survey of the benefits of the Voyager and other missions which are obtainable by interagency arraying, and of the technical and organizational efforts needed to achieve these benefits.

II. Missions Other Than Voyager

In addition to Voyager's needs which motivated this study, a number of other applications for interagency arraying were examined. These included both other possible flight projects and ground-based radio science observations of several kinds.

Table 2 summarizes the opportunities that were identified for ground-based observations. Planetary radar, for example, can be done using Goldstone for the transmitter, and one or more large observatories as receiving stations—if the needed frequency compatibility is maintained. Some work of this type has been done in the past at S-band, using DSS 14 as the transmitting and Arecibo as the receiving site. The table identifies the three main categories: Planetary Radar, SETI (Search for Extraterrestrial Intelligence), and Interferometry—either VLBI, or connected-element interferometry using the real-time links that would be installed to implement the interagency arrays. The table also indicates in each case the facilities which would be of greatest benefit, the science drivers for their use, and the main items of instrumentation which would be required.

The currently understood mission sets, as represented on Figs. 4 and 5, were examined for their potential need for interagency arrays. In general, the base mission set was designed to operate adequately into the antennas of the DSN alone, and nothing has really occurred to change that, or to create major benefits from substantially increased ground aperture beyond that planned for the DSN of the late 1980's. Voyager, of course, has encountered a change, because it was basically designed for the Jupiter and Saturn Encounters, much closer to Earth than Uranus and Neptune.

The ISEE-3 spacecraft has also undergone change, from its initial role as a solar wind observatory in the libration point between the Sun and Earth, to its planned usage in the close vicinity of the comet Giacobini-Zinner in 1985. At its design point, the spacecraft was 0.01 astronomical units (AU) away from Earth, and at the cometary encounter it will be about 50 times further at 0.46 AU away. It was supported with very high signal margins by the GSTDN at the libration point, but will be straining the DSN capabilities as a comet mission. The encounter with the comet will be at the northern declination of +23 degrees, so that the planned Japanese 64-meter antenna and Arecibo could both provide an excellent supplement to the support by the DSN.

The set of potential future missions was examined for candidates for support by interagency arrays which would be similar to that needed by Voyager. This mission set is dominated by Mariner Mark II missions, which are constrained in data rate, deployed to close-in targets, or both. The Mariner Mark II EEIS (End-to-End Information System) Team helped in examining this mission set for benefits of interagency arraying. Of these missions, only one, the Titan Flyby/Titan Probe, showed even modest benefit from arrayed support. For this mission, it was found that "interagency array allows reduction of precious spacecraft power to telecom" (Ref. 1). The mission is characterized by two short intervals of fairly intense data gathering, the probe entry phase first, and then the radar mapping phase as the carrier spacecraft flies past Titan.

In addition to the examination of specific missions, the interagency array study team also spent some time in brainstorming about types of missions which could follow the present or presently planned missions. These mission types included intensive Mars or Venus exploration programs, as well as missions to small bodies, and orbital missions to the outer planets. If Voyager does the job expected of it in 1986 and 1989, there will probably not be another reconnaissance type mission to Uranus or Neptune. Even if there is such a mission to an outer planet, it will probably be *designed* directly for that usage, with a telecom capability which is consistent with support by the DSN's own apertures. Planetary orbital missions could motivate additional capability within the DSN, but would not be candidates for arrayed support by observatories because of the extensive coverage required.

In summary then, it appears unlikely that another U.S. mission will arise within the near future which will derive as great a benefit as Voyager from interagency arrays. Cross support, or the exchange of support between various space agencies for each others' missions, is a very different matter, and suitable arrangements with Japan's Institute of Space and Astronautical Sciences (ISAS), or with other space agencies of the world, would effect an increase in the pool of antenna facilities which can be called upon to support space missions. This would both enable better mission support during intervals of heavy support load and smooth the workload on individual facilities. Exchanges of support can also be beneficial in situations which are geometry-dependent, as in supporting a U.S. spacecraft at northerly declination from the Japanese 64-meter station and a Japanese spacecraft at southerly declination from the Canberra Deep Space Communications Complex (DSCC). Emergency situations are yet another matter, and if the various non-DSN facilities were easily configured to be capable of spacecraft observations, it would seem perfectly natural to seek their support in reacting to a greatly diminished spacecraft signal level.

III. System Requirements and Performance for Voyager

The Voyager flight to Uranus and Neptune is the primary near-term driver for the expanded performance enabled by interagency arraying. The objectives of the missions to Uranus and Neptune are, generally, to extend the comparative studies of the outer planets to include the environment, atmosphere, surface and body characteristics of the planets and the characteristics of one or more of their satellites; to determine the nature of the rings of Uranus; and to search for rings at Neptune. Typical specific scientific objectives to be addressed include measurements of the gross morphological structures of the planets and satellites; determination of the atmospheric composition, structure, and dynamics of Uranus and Neptune; determination of the Neptune rotation period; detailed magnetospheric and plasma studies; a study of the satellite surface features, temperatures, and possibly the Triton atmosphere; a study of the Uranus ring system; and a study of the Neptune rings, if they exist. More detail on this subject may be found in the Voyager Project plans for Uranus (Ref. 2) and Neptune (Ref. 3).

The Voyager science data requirements for the Uranus encounter can be succinctly stated as (1) continuous general science data throughout the entire encounter period, in order to characterize the spatial and temporal variations of the fields and particles surrounding the target planet, and (2) imaging observations during the near-encounter period which are adequate to provide a basic characterization of Uranus, its satellites, and rings.

By assessing the specific imaging targets at Uranus, the project science office estimated that on the day of encounter, some 50 effective-full-frame-images (EFFI) should be allocated to the planet, 121 EFFI allocated to the satellites, and 157 EFFI allocated to the examination of the rings, for a total of approximately 330 EFFI. For several days immediately surrounding the encounter day, the image count requirement will also be in the neighborhood of 300 EFFI per day. During the observatory phase, a few months preceding encounter, a return of 30–50 EFFI each day would be considered satisfactory.

The specific target-based assessment has not yet been done for the Neptune encounter, but it is strongly believed that the required image count will be on the order of some 300 EFFI on the encounter day. Although there are no known rings at Neptune, the important search for rings, coverage of the planet Neptune itself and of the large satellite Triton will almost certainly require the 300 EFFI per day at encounter.

These needs can only in part be met by the support available through the capability the DSN will have in 1986 or 1989, in concert with the enhancements being made to the onboard Flight Data System software. The part of these needs which cannot be met by the DSN forms the primary driver for the interagency arraying system. That system must provide the capability to receive the Voyager's X-band signal at the selected sites and to reduce these signals to baseband so that they may be transported to the DSN site in longitude. That system will further provide the capability to array the baseband signals from the non-DSN facilities with those of the DSN site in real-time via microwave or satellite link. It will also provide the capability to combine recorded baseband signals from each non-DSN site with concurrently recorded signals from the DSN site in longitude. Both real-time and recorded-signal arraying must be provided to ensure adequate reliability for the overall arrayed aperture.

Figure 6 shows the planned performance of the DSN as it would be when arrayed with a number of the plausible candidate observatories for the support of Voyager at Uranus Encounter. The horizontal axis of this figure is labeled in GMT hours on the encounter day, January 24, 1986. The left-hand axis is calibrated in dB-Hz of data power to noise spectral density. The solid arcs of the figure show the expected received signal-to-noise ratio for the X-band Voyager signal under 90% confidence conditions. This means that for at least 90% of possible situations, including predictable variations in the equipment parameters and weather as modelled by day-quarter and year-quarter, the Voyager's signal as it is received will be at least as strong as that indicated. The arrayed performance of Parkes with the DSN Australian complex is also shown as a solid line, because we are committed to bringing that capability into existence for the Uranus Encounter. The American longitude array of the Owens Valley Radio Observatory with the DSN's Goldstone Complex is being pursued by the DSN Advanced Systems Program as a possible demonstration vehicle for arraying technology, while the array with the Bonn 100-meter is not being actively pursued at this time.

The weather statistics assumed for Fig. 6 for each of the DSN sites are the standard MRI (Meteorological Research Incorporated) quarterly weather model which is documented in the DSN Interface document (Ref. 4). For the non-DSN sites, the weather statistics were approximated by those of a DSN site with similar rainfall and temperature averages, as represented by the Hammond world almanac, or by other data as available. As the DSN models are believed to be conservative, this should result in a conservative estimate of arrayed performance. Work is needed to refine these estimates prior to encounter. In all cases, the statistical independence of the weather patterns at the DSN and non-DSN arrayed sites was included, and modestly increased the arrayed performance. The functional availability of the various array elements was also included.

At each longitude, the DSN performance shown corresponds to the arrayed performance achievable with the full DSN configuration as it will be in 1986. At Madrid, the array is the same as it was for the Saturn Encounter, with the 64-meter and the standard-performance 34-meter antennas. At Canberra and Goldstone, the array consists of three antennas at each site, which includes the preceding two, plus a new, specially shaped high-efficiency 34-meter antenna. It should be noted that the arraying configuration being developed will also be capable of non-real-time arraying of the different longitudes of the DSN, should it prove operationally desirable to do so. The performance of such an array during the overlap between Goldstone and Canberra would rise to a peak at the equi-power points of the Goldstone and Canberra performance curves. It would rival the Canberra-Parkes arrayed performance at peak value, but provide only a few short hours of coverage.

The right-hand axis of Fig. 6 is labeled at the threshold levels of signal-to-noise ratio for the data rates which will be used at the Uranus encounter. Table 3 is a partial catalog of these data rates, together with their contents in terms of science data return. The data rates of 29.9 kbps, 19.2 kbps, and 7.2 kbps exist today and were available at the Saturn encounter. The other data modes are under development now by the Voyager Project to improve the return from the Uranus and Neptune encounters. The full catalog of applicable data rates and modes may be found in Ref. 5. The new data rates involve the use of an onboard Reed-Solomon encoder to provide very low bit error rates with only modest redundancy. For the true rate of 3.6 kbps of the general science data, this means that a transmitted data rate of 4.8 kbps can be used instead of the 7.2-kbps data rate which was the primary coded data rate when the Voyager was launched. The penalty of the Reed-Solomon code is in greater complexity, in both spacecraft encoder and ground-based decoder. The new imaging data rates all involve use of image data compression, which is established in the Voyager spacecraft by operating the redundant Flight Data System (FDS) processors as a dual parallel processor. Since the dual processors were initially provided to give adequate assurance that at least one of them would be functioning at the Saturn encounter, the availability of that dual processor mode is an item of some concern. Nevertheless, with the exception of a few minor components, all four FDS units on the two spacecraft are operable today, giving rise to a current assessment of a 80-85% likelihood that the dual processor operation will be available at Uranus, and a 65-75% likelihood that it will work for Neptune.

The fulfillment of the requirement for continuous general science data can be assessed from Fig. 6. It is fully satisfied if the 4.8-kbps data rate is operative. If the existing 7.2-kbps data rate must be employed instead, there are coverage gaps totalling approximately four hours at the edges of the Madrid pass. Arraying with the Bonn Observatory would fill in only a small part of that.

Assessment of the imaging return from a planetary encounter is a considerably more complex process, involving as it does more than a half-dozen possible data rates, plus the option of recording either compressed or uncompressed images onto the spacecraft digital tape recorder. The assessment was carried out for the Voyager Mission Planning Office by S.J. Kerridge by using a linear programming technique to optimize the predicted return within the constraints of the telecommunications performance curves of Fig. 6, the available data rates, and the available storage capacity of the digital tape recorder. Details of this process are beyond the scope of this document, and may be found in Ref. 5.

The results of this assessment for the return from the Uranus encounter appear in Table 4. The most favorable and least favorable spacecraft state are indicated here. The most favorable state, with both Image Data Compression (IDC) and the Digital Tape Recorder (DTR) operable has an estimated 72% likelihood, while the least favorable state, with neither IDC nor DTR has an estimated likelihood of less than 2%. Encounter day differs from the steady-state operations in that the DTR, if operable, will be filled to capacity with the irreplaceable data from the closest approach period, and played back on succeeding days. The steady-state condition represents the operation on the days approaching encounter when any data recorded on the DTR must soon be played back to leave the DTR empty for filling at closest approach. Without the DTR operable, all images must be returned in real-time, so that the only difference between encounter day and steady-state results is the specific data modes which are used based upon science criteria.

As can be seen from this table, the addition of Parkes Radio Telescope to the Australian array effects a 10% to 15% increase in the images returned by a healthy Voyager, and brings the encounter day return up to almost the target level of 330 EFFI. The benefit from Parkes support is more dramatic if neither IDC nor DTR are available. For this very unfavorable but possible condition, the addition of Parkes more than doubles the image return to an estimated 90 EFFI. The benefits from augmenting Goldstone with the Owens Valley Radio Observatory or Madrid with the Bonn 100-meter telescope are neither one as significant to the objectives of the Voyager encounter with Uranus, but are shown in Table 4 for comparison

The baseline plan for the DSN configuration of 1989 is shown in Fig. 3, together with the largest of the candidate observatories for support of the Voyager Neptune encounter. The arrayed performance of this network is shown in Fig. 7, together with that available through arraying with the primary candidate observatories. Similar to Fig. 6, this figure indicates the 90% confidence telecommunication performance curves for the day of Neptune encounter on August 24, 1989. For this encounter, arraying with Parkes is needed to support the 14.4-kbps IDC data rate. As was the case at Uranus, almost continuous general science is supportable by the DSN at the 4.8-kbps data rate, but not if the 7.2-kbps data rate must be used.

The assessment of imaging return from Neptune was performed by the same linear programming algorithm as was used for Uranus, and is shown in Table 5. There are clear benefits in terms of image return for all spacecraft states from arrayed configurations involving Parkes, the Japanese ISAS 64-meter facility, and at least the "partial" configuration of the Very Large Array (VLA). The step-up to the maximum VLA configuration also has substantial benefit for the weakened-spacecraft condition. At Neptune, the anticipated likelihood of both IDC and DTR being available is 54%, and the likelihood of neither being operable is less than 7%.

There is, in addition, a need to retain some measure of protection against deterioration in the spacecraft telecommunications link in ways not covered by potential failure modes of the Flight Data System. Such deterioration can result from degradation in the spacecraft's high power X-band transmitter, or its RTG power supplies, or from antenna pointing losses resulting from accommodating the unrelated problems with the instrument scan platform. Link deterioration can be on the order of 1-3 dB with a risk level of perhaps 5% for each of several sources; much larger losses are possible but with lower risk. Such concern is best accommodated by providing at least one receiving facility which is capable of satisfactory support despite the 1-3 dB potential deterioration. The Parkes-Canberra array fulfills this need for the Uranus encounter. The VLA with maximum capability would be ideal for the Neptune encounter if it were readily achievable. The Japan-Parkes-Canberra array appears to provide another effective and achievable answer to this concern for Neptune. As shown on Fig. 7, the array of Goldstone with the VLA at approximately half maximum capability will extend the duration of Voyager coverage at this level.

Figure 8 shows the functional block diagram for the interagency arraying capability. Both real-time and near-real-time operation are included as outlined previously. The preferred mode of operation is to use the real-time array as the primary path, with the near-real-time as a backup. This operating mode requires wideband analog RF links, but provides continuous real-time imaging, even if the DSN site alone cannot, by itself, support the spacecraft link. It also does not require the transport or processing of the tape recordings unless the real-time intersite link is inoperative.

The high cost of the intersite link would be eliminated if we chose to use near-real-time combining only. However, there would be no real-time science data and thus no visibility to enable experimenters to adjust instrument parameters, unless the weather were exceptionally benign and the telecommunications link into DSN site alone were of itself above threshold. This mode of combining also requires the operational burden of regular transport and processing of the tape recordings, and inserts a new single-point-of-failure in the form of the recorders which would not themselves have backup. Furthermore, our experience in establishing correct operation of dual-site non-real-time support operations in VLBI (Very Long Baseline Interferometry), without concurrent real-time verification of the configuration, has been dismal and would be thoroughly inadequate for support of vital planetary encounter telemetry. Instrumentation of the arrayed sites to provide adequate visibility and verification without the real-time link is being explored as part of the Parkes/Uranus activity in an attempt to make the near-real-time-only mode into a workable option.

As outlined above, substantial evidence has been gathered that both real-time and near-real-time capability must exist to provide adequate support to the Voyager encounters (Ref. 6), and until demonstrated otherwise, this combination will continue to be the basis for all interagency array planning.

IV. Organizational Interfaces

It was clear from many considerations that there was no uniform and absolute rule which could be used to characterize the organizational aspects of each instance of interagency arraying. While a generalized model is possible, the details of the interfaces will in each instance be specialized to the needs of the involved agency. In establishing the arrangements for interagency arraying, we must and will seek to establish associations and interfaces that are beneficial to all agencies involved. Permanent ties will be sought with other space agencies, such as Japan's ISAS. Shorter-term relationships focussed by a specific goal such as the support of Voyager at Uranus, or the making of a ground-based interferometric radar map of Venus, or other astronomical measurements, seem more appropriate for the radio astronomy observatories.

There are four distinct categories of agencies which operate the primary candidates for interagency arraying operation. Each of these has special needs, which must be considered in establishing the organizational interfaces, and special strengths which can be relied upon. These four agency types are catalogued below:

U.S. National Observatory	NRAO-VLA
U.S. Academic Observatory	OVRO
Non-U.S. Radio Observatory	Parkes/Bonn/Nobeyama
Non-U.S. Space Agency	Japan-64-m/Weilheim-30-m

The interfaces to non-U.S. agencies will require formal agreements tailored to fit under the umbrella of pre-existing international agreements, as is the case for the Parkes array. For all of these, management and administrative interfaces will involve NASA Managers, the JPL Assistant Laboratory Director for Telecommunication and Data Acquisition (TDA), and the TDA office managers in interaction with their counterparts at the operating, or host agencies. These interfaces are supported by the current TDA structure and procedures.

The engineering interfaces for establishing an interagency array are formally managed via the TDA Engineering Office. The applicable procedures, however, are necessarily very different from those usually used in DSN implementation, and are streamlined and respectful of both the capabilities and interests of the host agencies. The engineering interfaces with each agency are focussed during development by a project engineer/task manager who is responsible for the success of that particular array element. Because each candidate host is unique, significant interaction will be required between the engineers of the JPL technical divisions and those of the host agencies. This will need at least good electronic communication, as well as increased travel or personnel exchanges.

Operations interfaces for the flight projects are similar to those which exist now. The "TDS Manager for Project" is the focal point for all joint mission support. The coördination of operational events and activities will be performed by DSN operations, within the constraints of the agreements negotiated with each host agency. Operational coördination of the arrays will occur via the combining center at the DSCC in-longitude. Communication and coordination for both operation and implementation can be facilitated by in-longitude visits between DSN and host-agency personnel. A global forum would also be useful in this regard, similar to, or perhaps as a part of the Station Director's (STADIR) Conference.

V. The Tidbinbilla-Parkes Array for Uranus

The array of the Australian DSN complex with the Parkes Radio Telescope is being established for the support of the Voyager at Uranus. It is the pathfinder project for interagency arraying, as it will be the first time that such support will be provided for a major planetary encounter. The overall requirements for configuring an interagency array were described in section III. The Parkes array is being implemented as a straightforward extension of current DSN technology in order to assure support for the Voyager data return at Uranus. Specific items of equipment design will be new for this application, such as the telemetry recording subsystem utilizing VLBI recorders, but the real-time system design follows that which was experimentally developed in the early 1970's, demonstrated with arrayed reception of Mariner 73 at Goldstone, and more recently implemented throughout the DSN and used to support the Voyager Saturn encounter (Ref. 7).

The implementation process for the Parkes array is expected to be much streamlined as compared to conventional DSN practice for long-term implementations. Specific details of this process are still to be negotiated. In considering this, it should be remembered that the Parkes array will not be implemented and then left in place to be operated and maintained by a long series of different operational personnel; it will instead be established and operated for a short (but important) event under the guidance of its designers. Rationale and general guidance for the steamlined implementation process may be found within the reports of the "Parkes-Canberra Telemetry Array" Task (Ref. 8). This process is aimed at providing cost-effective implementation and operation of a unique installation, which nevertheless is of adequate quality to assure viable spacecraft support. It is assumed throughout this report that this steamlined implementation process will be applied to all of the non-DSN facilities which are instrumented for arraying support.

The timetable for on-site activities at Parkes is shown on Fig. 9. Radio astromony, shown on the bottom line of this figure, is the primary business of the observatory, and naturally dominates the overall time, except for intervals surrounding the two Voyager encounters plus the test and demonstration interval in late 1984. In addition to the Voyager, the Parkes Radio Telescope will be supporting the Giotto spacecraft, which is being sent by the European Space Agency (ESA) to Halley's Comet. The support interval in 1985-86 will be shared between these spacecraft, with Voyager dominating near its encounter in January 1986, and Giotto dominating near its encounter a few weeks later. The intersite link between the Parkes Observatory and the DSN Complex, which is about 350 km to the south, will be installed to provide real-time arraying capability, but will be available for radio astonomy use also, and retained for that purpose following the Uranus encounter. Figure 10 shows the relative locations of Parkes, the Australian DSN complex, and the planned intersite link. The agreements which enable the support of Voyager by the Parkes Radio Telescope also provide for a significant amount of support for the Australian radio astronomy community by the DSN, which is anticipated to be used for real-time interferometry employing Parkes, the DSN antennas of the Canberra Complex, and the intersite link.

Figure 11 shows the functional elements of an interagency array as typified by the Parkes-Canberra array. Two elements of this drawing were added to generalize it, and are not part of the Parkes configuration: the satellite communication link for real-time arraying with large intersite distances, and the non-real-time combining via the VLBI correlator in Pasadena. The satellite link is applicable to an array between the Japanese 64-meter station and the Australian DSN site. The non-real-time arraying via the VLBI correlator is being explored under the DSN Advanced Systems Program, but is not critical to the operation of the array. It could be used for arraying between longitudes, or as an off-line backup for the real-time/near-real-time systems. At Parkes, the low-noise amplifier, the receiver front-end, and an upgrading of the antenna surface for X-band operation are being provided by ESA as part of their preparation to support Giotto.

The elements shown in the upper left one-third of Fig. 11 reside at the observatory, while the rest of the mainline elements are at the DSN complex in-longitude. At the observatory, the spacecraft signal is coherently detected to produce a baseband signal consisting of the subcarrier (360 kHz for Voyager) modulated by data, which is then both transmitted over the real-time link to the DSN site, and simultaneously recorded. At the DSN site, this signal is treated virtually the same as a signal from a DSN antenna, in that it and the combined signal of the DSN subarray are delay-adjusted into agreement and then coherently added before subsequent demodulation of the subcarrier, decoding, and telemetry processing.

With the configuration shown, we have the option of replaying the recorded tapes via the intersite link for near-real-time backup operation, as well as the operation of transporting the observatory tape recording, should there have been problems with arraying during the pass. Technical performance of the array is expected to be excellent, with an allowed degradation budget of 0.2 dB for the combiner itself, and another 0.2 dB allotted for either the intersite link or the recording and playback processes.

VI. DSN Advanced Systems Program Plans for Arraying

The DSN Advanced Systems Program Office has defined plans for development of arraying technology which will be applicable to the Neptune encounter. The Owens Valley Radio Observatory (OVRO) is to be approached as a test bed for the demonstration of the potential improvements in both technology and cost, and for field demonstration of this capability through support to the Voyager at Uranus on a best-efforts basis. Specific negotiations for this work are now in process.

The Advanced Systems Program intends to provide a complete receiving system, including telemetry equipment, which is suitable for arraying a radio observatory site with the DSN. This effort will include developing fieldworthy R&D equipment for demonstration at the OVRO site prior to the Voyager Uranus encounter. It will provide a focus and a schedule driver for selected advanced systems activities. Equipment developed will be transportable to other facilities for future encounters or demonstrations, if needed. The proposed demonstration is an R&D activity with no formal commitment to the Voyager project.

In general, technology planned for demonstration with an OVRO array is already planned or under development by the Advanced Systems Program for future use by the DSN. To reduce costs, existing or surplus equipment will be outfitted for the OVRO installation wherever possible. For the front-end area, a new focal point feed will be employed which has the potential for achieving an efficiency of 60-65% with a 17 kelvin system temperature. A surplus R&D X-band traveling wave master (TWM) will be modified to achieve dual-channel operation for polarization diversity and to fit within the package design recently employed to install a K-band (22-GHz) TWM at OVRO. The dual-channel TWM can accommodate a switch to the alternative polarization of the Voyager spacecraft's backup transmitter by simply switching inside the receiver instead of the microwave area. Existing support equipment for the K-band TWM will be used for the X-band TWM. If the conversion to a Cassegrainian feed system, which is currently being considered, occurs prior to the arraying demonstration, then the new focal point feed will not be needed, and other parts of the task will also be simplified.

The back-end of the array of Goldstone and OVRO will provide the opportunity to demonstrate symbol-stream combining, and also applicable technology from the advanced receiver development, including digital phase-locked loops, ephemeris aided tuning, etc. For symbol stream combining, the received signal at each site is processed through the subcarrier demodulation and symbol detection processes before being sampled and transported to the common combining point for decoding. Preliminary analysis indicates that symbol stream combining is not only feasible, but may also be able to perform better than the predetection combining currently employed. The initial rationale for exploring symbol stream combining is still valid: to reduce the bandwidth of the signal to be transported by intersite link or on tape from a remote site to the DSN combining location, in order to reduce the cost of such electronic or physical transport.

The schedule goal of the Advanced Systems Program is to demonstrate the arraying with OVRO prior to the Voyager Uranus encounter. In fact, the basic demonstration should be by the spring of 1985, so that it could be accommodated into project planning, if appropriate. The non-real-time demonstration is totally within the Advanced Systems Program resources. A real-time demonstration will require the provision of a 224-kbps digital link from Owens Valley to Goldstone, which is not within the Advanced Systems funding. The detailed milestone schedule leading to this demonstration will be established during the program planning negotiations which are occurring in early 1983. Both funding and schedule for this activity are subject to the usual review by JPL and NASA management as the details of the Advanced Systems Program are refined.

VII. Instrumentation of Other Facilities for Voyager at Neptune

Other major antenna facilities of the world were examined to determine the effort and equipment needed to instrument them for arraying with the DSN in a configuration analogous to that being used to connect Parkes with the Canberra complex. Chief among these were the Bonn 100-meter telescope, the Japanese ISAS agency's 64-meter station, and the National Radio Astronomy Observatory's Very Large Array. In each case, the arraying configuration and functional block diagram is the same as that employed for Parkes: including both real-time and near-real-time arraying, and using the VLBI recorders for the backup recordings. Engineering for this design is a routine step forward from that of the Parkes array, which establishes a reference mode in which we can be well assured of success. But as we assume there will be success within the Advanced Systems development work on arraying, so then we should expect the details of the arraying design for Neptune to change to absorb the improvements demonstrated there. Until such demonstration, however, prudence dictates that the main pathway plan for Neptune arraying should directly follow the Parkes design.

In general, the equipment configuration for each installation is based upon a JPL design, even though when all details of in-place or planned equipment are known, the better course may be to utilize equipment developed by the facility itself. The engineering process is assumed to be the streamlined one being pioneered with Parkes.

The Bonn 100-meter telescope and the Japanese 64-meter antenna are both very similar to Parkes in that each is a large single reflector which by itself would contribute a significant addition to the array aperture. Loss of that addition would result in either a direct loss of data, or a change in Voyager data rate. To reduce the risk of loss to an acceptable level, independent redundant components are required in the cryogenic front-end amplifiers, and perhaps elsewhere in the system. Traveling wave maser (TWM) amplifiers are appropriate to the Japanese station, where the Voyager is visible for almost 8 hours per day. Other spacecraft will be subsequently supported by this antenna, and will benefit from the very low system temperatures which are achievable by TWMs. It is unfortunately true that the Bonn 100-meter telescope is far enough north that it can only observe the Voyager spacecraft for approximately 5 hours per day, and then only through a significant amount of atmosphere. While it is true that under clear dry conditions a TWM will provide substantially better performance than any other known amplifier, missions are not designed to operate only in clear conditions, but must accommodate (at least) the 90% weather condition. Under 90% conditions, as we today perceive the Bonn weather statistics for August 1989, there is only a very modest benefit to Voyager for choosing a TWM over a (much cheaper) cryogenic FET amplifier with a 40-50 kelvin clear-weather system temperature.

Our engineering assessment proceeded under the assumption that all equipment which is specialized to X-band operation for tracking of spacecraft would be JPL-supplied. This includes the feed, the microwave plumbing, the applicable low noise amplifiers, the receivers, the recording and communication interfaces, and applicable instrumentation and monitor/control equipment. A VLBI recorder is also anticipated to be needed for the Japanese station. It should be noted that there is presently no commitment to JPL supplying any specific components, and that in fact cooperative agreements would be sought for the equipment development. The generalized schedule for the implementation is analogous to that being pursued for Parkes, and assumes a significant amount of contracting for fabrication of needed equipment. The overall effort occupies on the order of four years, and for the Neptune encounter in August of 1989, significant in-depth engineering work must start by FY 85. Onsite demonstration of arraying with the in-longitude DSN facility is strongly recommended for mid 1988, about a year in advance of the Neptune encounter.

The major agreements needed to enable the Voyager support at Neptune should be in place by mid 1985 in order to avoid potential problems in the engineering process. Figure 12 shows a generalized schedule applicable to the Bonn 100-meter telescope, to the Japanese 64-meter station, or to most other single-antenna facilities which might be considered for Neptune support.

The approach considered for the Very Large Array near Socorro, New Mexico, follows the Parkes design to the extent that such is possible with an array of modest-sized antennas. The back end of the system which performs phase locked detection and demodulation of the spacecraft signal to baseband in preparation for combining, the combining process at Goldstone, including both real-time and near-real-time options, the recording on the VLBI recorders, and the phase-lock receiver/coherent detection processes are all directly derived from those of the Parkes array. As will be discussed shortly, there are a number of options available for the front end of the VLA system, each with a different capability and complexity.

The VLA is an array of twenty-seven 25-meter antennas in a triradial configuration in the high New Mexico desert. Each of these antennas could be equivalent to about 18% of the DSN's 64-meter antenna aperture, if the VLA antenna were outfitted with a TWM. The primary role of this array is developing maps of radio-bright objects in the sky, and it incorporates a large mapping processor which is capable of cross-correlating the 351 (= 27*26/2) baselines of the array in real-time. One of the optional products of this mapping processor is a combined output which represents the coherent sum of the signals being received at each of the antennas. This combined output of the mapping processor would represent about four of the DSN's 64-meter apertures if all of the VLA antennas were outfitted with TWMs, or about two apertures if cryogenic FETs were installed. Because of the atmospheric noise effects, as noted earlier with the Bonn observatory, the effective performance of the VLA with FETs is expected to be better than 70% of that with the same number of TWMs for the Voyager encounter. Also, an improvement of about 1 dB in effective performance for the reception of spacecraft signals should be possible with either low noise amplifier if a specialized combiner and parallel signal path is installed. While this improvement potential is interesting, our current estimate of the costs involved makes this a nonviable option.

While there are conceptually very many options to choose from for the VLA configuration, they are all categorizable into a few option families, and only a few specific options need be examined to adequately characterize the entire collection. Our study approach was based upon the assumption that the maximum configuration should be protected and made available to be implemented if it became clear after the Uranus encounter that there was significant risk that the Voyager's image data compression would not be available at Neptune. This capability would have required TWMs in all VLA antennas, plus the specialized combiner and also would have required significant start by mid 1983 to remain viable. A schedule consistent with this approach is shown in Fig. 13. On this schedule, the actual decision between maximum capability and approximately half-capability would be deferred until just after the Uranus encounter, and could be based then upon an updated estimate of the likelihood that data compression would be operable at Neptune.

However, assuming that we can safely base the decisions regarding the Neptune encounter support upon the estimates available today for the viability of the data compression at Neptune, then the rational choice for a VLA configuration is one which can provide approximately half the maximum capability. Strong gains exist for Voyager's image return by providing this capability over the American longitude, whether the data compression is operative or not. As noted earlier, stepping upward to the maximum capability at the VLA will also reap significant benefits in the absence of data compression, but will only provide mild benefits if the Voyager is in its "most likely" state with both the data compression and the onboard tape recorder operative. The recommendations of the study team, to be discussed in section IX, are for a VLA configuration with the half-maximum capability.

The VLA can be configured to about half of its maximum overall capability for Voyager signal reception by installing cryogenic FET amplifiers in all of the antennas. The FETs are significantly less expensive and easier to build and maintain than the same number of TWMs, and it is believed that major work for an FET-configured VLA can begin in FY 85. Such a delay will, however, virtually foreclose the option of achieving the maximum configuration with TWMs.

Figure 14 shows the VLA configuration for Voyager support as we envision it today, together with the option for a specialized combiner which would bypass both the quantization in the VLA's mapping processor and the 1.6-ms gap in signal reception per 52 ms which is used in the VLA to calibrate and control its front-end systems. As noted above, the current assessment is that this option is too expensive relative to its expected benefit to pursue seriously, so that the only items to be added to the VLA are the X-band low-noise amplifiers and down-converters at the front-ends, and the phase-locked receiver and coherent detector at the combined output of the VLA processor. Two channels of the VLA signal transmission and processing equipment are used: one with a 6-MHz bandwidth to carry the spacecraft signal at roughly full precision, and a second with narrower bandwidth to be used to control the differential phase and delay in the system.

Should the X-band TWM be chosen for installation into the VLA, the design of choice could be expected to be a dual-channel maser identical to that to be installed at OVRO, except for the packaging and instrumentation. Figure 15 is a sketch of this design, incorporating a cryogenically cooled orthomode coupler and a dual-channel TWM derived from the DSN TWM design by segmenting it into two independent halves, and supplementing the gain of each half by an output FET amplifier. As shown in Fig. 16, the standard DSN X-band TWM consists of four quasi-independent structures which are usually cabled end-to-end to provide the gain and noise figure specified for the DSN. Splitting it into two independent units can be effected by a cabling change, along with providing the additional input/output couplers. There should be no problem in achieving an effective zenith system temperature below 20 kelvins with this configuration, which is virtually the same as that of the original DSN configuration.

The X-band FET was not explored to the same level of detail as was the TWM, but related NRAO experience was considered. In the currently planned development of the transcontinental Very Long Baseline (VLB) Array by NRAO in collaboration with Caltech (Ref. 9), cryogenic FETs are included for X-band coverage. The anticipated system temperature is on the order of 50 kelvins with amplifiers built today, or about 40 K by 1986. Clearly, then, it will pay to delay commitment to hardware if FETs are to be chosen. Also, if FETs are to be chosen, there may be some benefit to NRAO or JPL, or both, if the design for the X-band amplifiers of the VLA shares common elements with that for the VLB Array.

VIII. Operations Scenario

The interagency array study team also sought to identify a reasonable operations scenario for arraying which would be consistent with that to be employed for Parkes, and also be applicable to the other facilities. The identified scenario depends upon several assumptions, derived from the Parkes planning, which are listed here:

(1) Data will be acquired and combined in both real-time and near-real-time.

(2) A member of the implementation team will remain "in-longitude" after the system is operational to serve as consultant to the operations team.

(3) The dividing line between non-DSN and DSN maintenance and operations functions will be at the receiver IF, as indicated in Fig. 17–this implies that host-agency personnel will maintain and operate the site-dedicated equipment, even if supplied by JPL, and that DSN-associated personnel will maintain and operate the "back end".

(4) Sustaining engineering will be via a suitable mechanism like the Equipment Support Agreement (ESA), instead of via full transfer.

(5) Operations of each array will be coordinated from the Deep Space Communications Complex in-longitude.

(6) All operations personnel for the array-specific operation will be recruited by the local DSCC.

These assumptions and the following notes define a general model for the operations scenario. It is recognized that each specific non-DSN facility which we will approach for the support of Voyager will be different in its interests and capabilities, and that details of the operations scenario will differ in each case, in ways that will be defined in specific agreements with the non-DSN facility and its sponsoring agency.

Figure 17 is an operations-oriented functional block diagram of a non-DSN facility configured for arraying with a DSN site. The general dividing line between the two main spheres of responsibility is shown explicitly. Implicit in this division is the assumption that each non-DSN facility will have a VLBI Mark III Data Acquisition Terminal (DAT). Staff support for the arraying operation involves three personnel in addition to the implementation engineer, who will remain in-longitude as the arraying consultant and general troubleshooter. At the DSCC, a dedicated station operator will be assigned responsibility for actual array monitor and control. At the non-DSN facility, an on-site Leadman will be assigned the overall maintenance and operation (M&O) responsibility for the DSN sphere of responsibility, and will perform in addition some operations monitoring. He will be supported by one M&O Tech whose responsibilities include the M&O of DSN equipment, providing backup to the Leadman, and tape operations. At the DSCC, the M&O of the array equipment will be by station personnel, as defined in the Equipment Support Agreement. Sustaining engineering of the equipment items at both the DSCC and the non-DSN facility will be specified in agreements with the facility managers.

Some support to the array will be required from the operations organization at JPL. This support includes coordination functions for additions to the operations plan as related to interagency arraying, coordination of predicts and communications, and general operation coordination and scheduling. Predicts are needed for the pointing of the non-DSN antenna and for specifying tuning for the receivers and time-delay for the arraying process. Some sustaining engineering will also be required, including at least maintaining the interface between various parties to the Equipment Support Agreements as well as Subsystem-Cognizant-Operations-Engineer support for System Performance Tests (SPTs) for the total array.

The nominal timetable for deployment of operations personnel at the non-DSN site is shown in Fig. 18. Two high-activity periods are indicated: one at encounter and an earlier one for SPTs about 20 weeks in advance of encounter. The actual duration and intensity of these periods is a negotiable item, but it should encompass the intervals surrounding encounter when the data of greatest intrinsic value would be obtained. As permitted by the equipment configuration, radio astronomy operation would continue throughout this period except during the agreed-upon intervals specifically dedicated to Voyager support. A large part of the installation and checkout of the arraying configuration and equipment could and would take place on a noninterference basis with respect to other activities at both the non-DSN and DSN sites.

IX. Summary and Recommendations

The interagency array study was brought to its conclusion in an open review on Friday, February 25, 1983. The primary decision needed at that time was for those items to be included in the DSN budgets and implementation planning for the years 1984–89. One decision which was particularly urgent was also painful—the choice between a pathway for the VLA which would protect the option of achieving its maximum capability for Voyager, but which needed an immediate start, and an alternative set of pathways which could achieve approximately half-maximum capability. Other decisions, whether to seek support from the Bonn or the Japan antennas or both, or perhaps from other facilities, would impact FY 85 and later budgets, but not require immediate starts.

The study team brought to this review a set of recommendations which were cognizant not only of the needs of the Voyager for Neptune, but also of the preparations in process for the support of the Uranus encounter, and of the ongoing need within the DSN to provide service to a substantial number of other missions. It became clear in this consideration that initiating the significant effort in FY 83–84, as needed for the maximum capability at the VLA, could jeopardize the near term work of the Network. Accordingly, such near-term start of detailed engineering work was not considered feasible, and the maximum-capability option was not recommended.

The recommendations of the study team, generally supported by the study steering committe, were as follows:

(1) Continue on present course with preparations for the Voyager Uranus encounter, including both the implementation of Parkes according to the planned streamlined process and the Advanced Systems demonstration of arraying technology at the Owens Valley Radio Observatory.

(2) Plan to seek support for the Voyager Neptune encounter from the Parkes Radio Telescope, from the VLA—configured to approximately half maximum capability (2.5 equivalent 64-meter aperture units), and from the Japanese ISAS 64-meter station.

(3) Retain the option to seek support for Voyager at Neptune from the Bonn 100-meter Observatory, should it become feasible and appropriate to do so.

(4) Establish interagency agreements and begin engineering on a schedule which is consistent with the chosen course of action. As noted earlier, the schedule for the recommended pathway requires implementation engineering to start by the beginning of FY 85.

The rationale upon which these recommendations are based can be seen in part in Figs. 19 and 20, which assess, each in different ways, the value of various interagency arrays to the Voyager as a function of their relative funding cost to DSN. Figure 19 shows the "capture value" of the various antenna options, as projected to the position of the Voyager spacecraft at its 1989 encounter with Neptune. Capture value is indicative of the total signal-energy-to-noise-density ratio that can be acquired from the Voyager during any one support pass by the identified antenna at one (optimum) realizable data rate. A capture value of unity could represent a mythical antenna offering 24-hour coverage equivalent to the current DSN 64-meter stations: 64-meter reflector with 50% efficiency and a 25-kelvin system temperature. The actual DSN 64-meter dishes are significantly less than unity capture value because they can only see the Voyager for a fraction of the day, and because their system temperature is degraded (for 90% confidence weather) to above 25 kelvins by the atmosphere the Voyager signal must penetrate.

On Fig. 19, the three DSN 64-meter stations are shown with zero incremental cost, to configure them for Voyager support, and with their capture value scaled to that which they will offer to Voyager at its position of -23° declination at the outer planet encounters. Identical in intrinsic capability, they differ in this figure due to their differing latitudes, and also to the different weather statistics peculiar to their site. The capture value for the various non-DSN facilities was derived with the same assumed weather statistics used earlier in Fig. 6. Their relative cost was derived from the engineering evaluation described in section 7, utilizing where applicable the analogy to the Parkes-Canberra array implementation. The Parkes cost itself is that applicable to the Uranus encounter, and does not include the TWMs and receiver components which are being supplied by ESA. The three straight lines on this figure for the VLA are approximations to the stairstep lines which would represent varying numbers of low noise amplifiers (FETs or TWMs) installed into the VLA antennas.

Figure 20 shows the potential imaging return for the Voyager at Neptune encounter for various interagency array options. The data portrayed on the vertical axis of this figure corresponds to Table 5 of section 3, but represents only the encounter-day strategy. Reference 5 may be consulted for more detail. The cost assigned to the Parkes array on this figure corresponds to only the replacement of the TWMs and receiver components which were supplied by ESA for the Uranus time frame. The costs assigned to the other arrays correspond to those of Fig. 19, including the partial VLA options which are shown as if achieved by TWMs. The various line segments of Fig. 20 serve merely to connect the points which represent specific arraying options. As in Table 5, Parkes is assumed to be a first step, to which can be added the Japan-ISAS 64-meter, the VLA in any of several possible configurations, or the Bonn 100-meter telescope. The slope of each line segment of Fig. 20 represents the "pictures-per-dollar" that can be obtained via the inclusion of the associated option.

Considering the Voyager imaging return in isolation, it is clear from Fig. 20 that the single most cost-effective interagency array for the Neptune encounter is that which was previously implemented for Uranus support; i.e., the Parkes Radio Telescope in Australia. That would still be true even if the full cost (Uranus + Neptune) of the implementation were considered. That is also true regardless of whether the spacecraft is healthy, with both image data compression (IDC) and the onboard tape recorder (DTR) operable, or whether it is weakened by one or more failures. The four probable states of the spacecraft data system are shown on Fig. 20, annotated by the current assessment of their relative likelihoods (Ref. 5). Argument can be made using the data on this figure that any one of the three primary alternatives should be considered as next after Parkes. The Japan 64-meter station is preferred because it provides the greatest imaging gain for the healthy spacecraft (the most probable state). The next best investment for the healthy spacecraft is the partial VLA configuration. Benefits in Neptune encounter data return continue to be obtained from adding capability to the VLA for all spacecraft states up to approximately the half-maximum capability level. Beyond this point, we are buying insurance that adequate support can be achieved despite deterioration of the spacecraft condition. The Bonn Observatory also is in the nature of insurance, in that its greatest benefits for Voyager imaging are obtained under conditions of a partially weakened spacecraft.

In summary, the Interagency Array Study team recommends that the arraying configuration for the Neptune encounter should consist of the full DSN aperture, plus Parkes, the VLA (at half-maximum capability), and the Japanese 64-meter station. This configuration will provide good imaging support of the Voyager at Neptune under current project expectations, as well as resilience to unanticipated deterioration in the space-to-earth telecommunications link.

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Table 1. Catalog of radio observatories

Institution	Location	East longitude	Latitude	Aperture	Area, m^2	Current Efficiency	Current T_{op}	Improved Efficiency	Improved T_{op}	% equivalent, 64-m	Remarks
64-m DSS	Standard for 86			64	3,217	50	25	50	25	100	
70-m DSS	Standard for 89			70	3,848			60	25	145	
Nuffield R.A.L.	Jodrell Bank, U.K.	358	+53	76	4,536	20	50	20	25	56	Old-inefficient far north
Franco-German	Spain	359	+38	30	707			60	25	26	mm-wave R/A instrument
MPIR	Effelsberg, FRG	006	+50	100	7,854	45	90	45	25	220	Needs LNA
	Bologna, Italy	012	+43	32 × 2	1,609			60	25	60	mm-wave; not built
CC-1	Yevpatoriya	033	+45	70	3,848	50	N/A	50	25	120	Needs TWM
CC-2	Ussurijsk	134	+44	70	3,848	50	N/A	50	25	120	Needs TWM
Japan 64m	Usuda, Japan	138	+35	45	1,590	60	N/A	60	25	59	Needs TWM
Japan 45m	Nobeyama, Japan	138	+35	64	3,217			60	25	120	Needs TWM
CSIRO	Parkes, NSW	148	−33	64	3,217	35	100	40	25	80	Needs TWM
OVRO	Big Pine, CA	242	+37	40	1,257	50	150	50	25	39	Needs TWM
NRAO-VLA	Socorro, NM	253	+34	25 × 27	13,253	60	N/A	60	25	494	Needs 27 TWMs
NRAO	Greenbank WV	281	+38	43	1,452	45	85	45	25	41	
Algonquin Park	Algonquin Park, Ont. Canada	282	+45	46	1,661	50	N/A	50	25	52	Needs
Haystack	Haystack, MA	289	+42	37	1,075	40	100	40	25	27	Lose 1 dB to Dome
Arecibo	Arecibo, PR	294	+18	305	73,062	40	N/A	40	25	1817	Useful only ±20 LHA and $\delta = -2$ to +39

Table 2. Additional potential users

Radio and radar astronomy			
Classification	Potential observatories	Science driver	Required instrumentation capability
Planetary radar	GDSCC with: VLA, OVRO, Arecibo (S-band), Australia telescope, Japan	Venus mapping Outer planet satellites and rings	X-band (8.45 GHz transmitter at GDSCC)
SETI	All	Confirmation, including position-finding Search special frequency bands RFI avoidance, e.g., interferometry	Receiver tunability (1–10 GHz) Data link to SETI processor at DSN facility
Interferometry			
VLBI	VLBI-consortium	Additional U-V plane coverage	RF frequency compatibility (including 22 GHz)
	VLBI-TDRS	Greater sensitivity for VLBI net	VLBI system compatibility, e.g., Mark III DAT at all 64-m DSN stations
Real-time	GDSCC-OVRO	Greater positional accuracy	Link bandwidth $\geqslant$ 6 MHz X-band link phase stability
	CDSCC-Parkes	Improved mapping	$\frac{\Delta f}{f} < 3 \times 10^{-3}$ rms and hourly drift rate RF frequency compatibility

Table 3. Voyager Uranus and Neptune data rates

Data rate, kb/s	Data type	Coding	Equivalent full images/hr
29.9	Full frame imaging	Convolutional	13
21.6	Compressed imaging + playback	Convolutional + Reed-Solomon	13 + 6
19.2	Half frame imaging	Convolutional	6
14.4	Compressed imaging	Convolutional + Reed-Solomon	13
11.2	Compressed imaging	Convolutional + Reed-Solomon	9
8.4	Compressed imaging	Convolutional + Reed-Solomon	5
7.2	General science and engineering	Convolutional + Golay	None
4.8	General science and engineering	Convolutional + Reed-Solomon	None

Table 4. Voyager Uranus picture return/day

Aperture	Spacecraft state		
	IDC, DTR		
	Encounter day	Steady state	No IDC, No DTR
Baseline GDSCC = 64, 34 S, 34 H CDSCC = 64, 34 S, 34 H MDSCC = 64, 34 S	290	205	40
Δ for augment "Australia" Parkes	30	30	50
Total (planned)	320	235	90
Δ for augment "Goldstone" OVRO	10	10	25
Δ for augment "Spain" Bonn	10	40	15

Notes: Daily return depends on DTR strategy and imaging constraints.

If S/C roll pointing is substituted for azimuth slewing, reduce numbers by 25%; additional telecom losses also likely.

H = high efficiency S = standard efficiency

Table 5. Voyager Neptune picture return/day

Aperture	Spacecraft state		
	IDC, DTR		
	Encounter day	Steady state	No IDC, No DTR
Assumed GDSCC = 70, 34 S, 34 H CDSCC = 70, 34 S, 34 H MDSCC = 70, 34 S, 34 H	255	95	35
Parkes	20	30	20
Total (planned)	275	125	55
Δ for augment "Australia" Japan	20	25	5
Δ for augment "Goldstone" VLA 2.5 aperture units	30	55	30
VLA 5.0 aperture units	35	60	65
Δ for augment "Spain" Bonn	0	25	10

Notes: Daily return depends on DTR strategy and imaging constraints.

If S/C roll pointing is substituted for azimuth slewing, reduce numbers by 25%; additional telecom losses also likely.

H = high efficiency. S = standard efficiency.

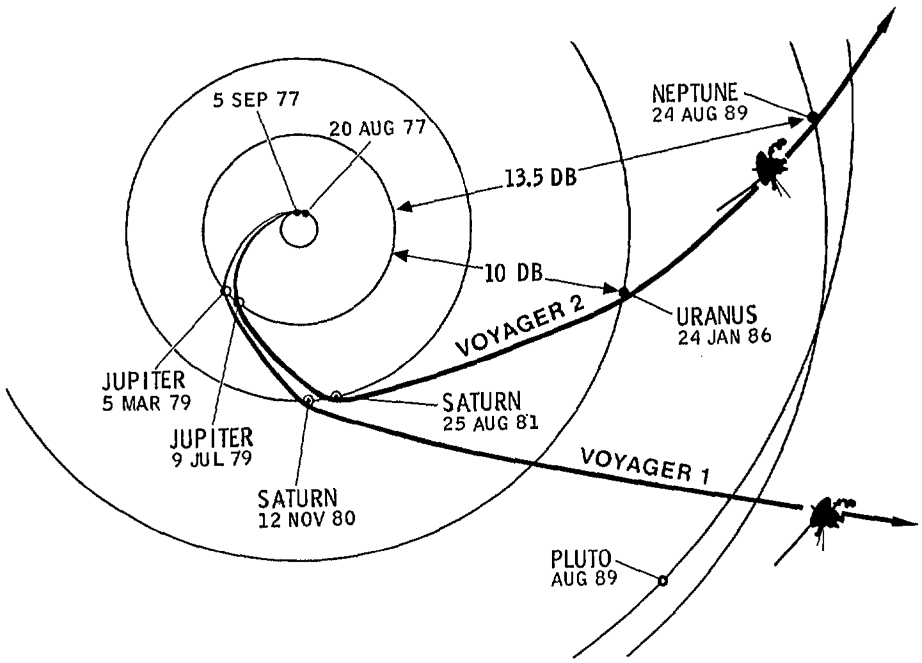


Fig. 1. Voyager heliocentric trajectory

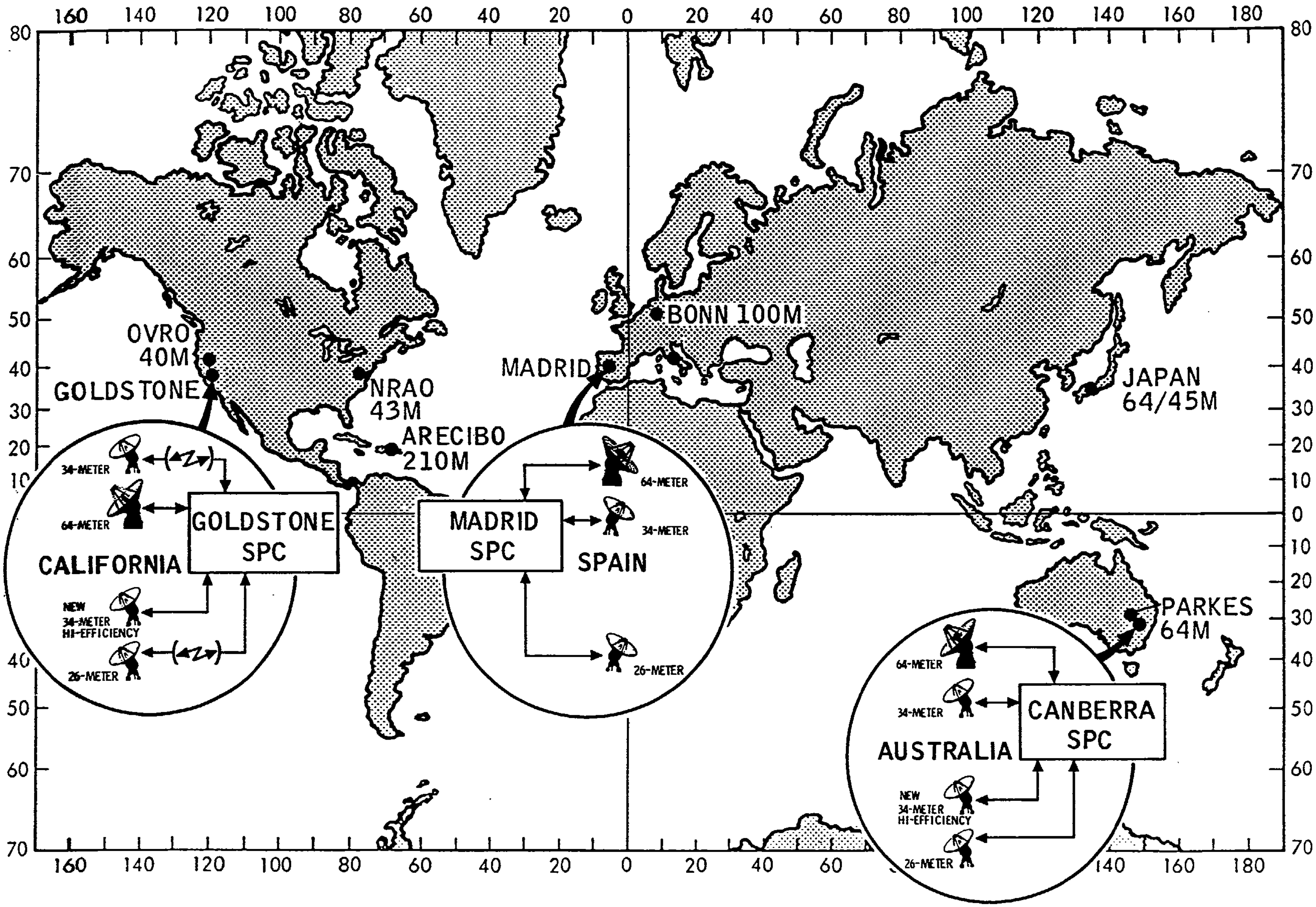


Fig. 2. 1986 Network configuration + candidate facilities

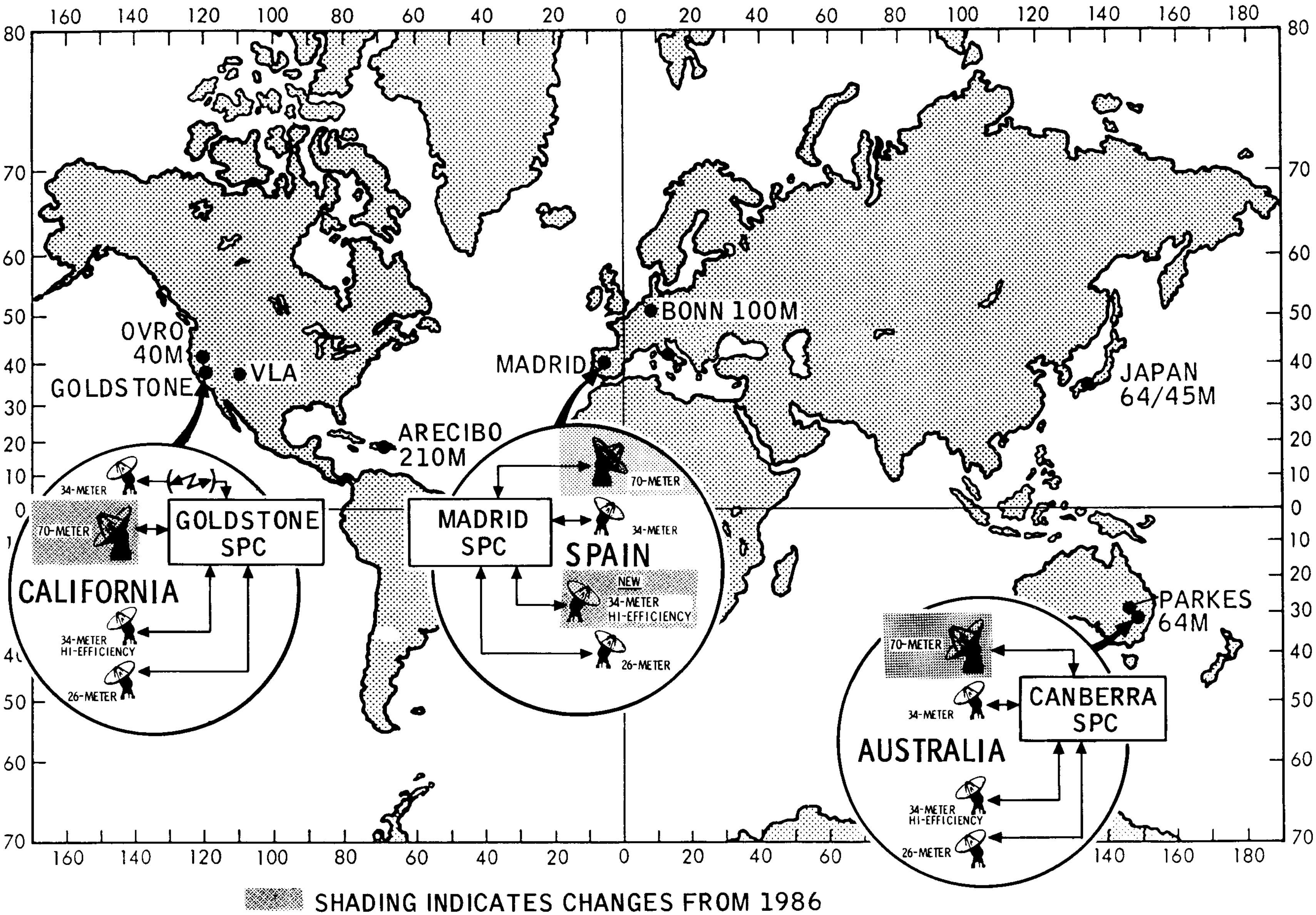


Fig. 3. Baseline 1989 network configuration + candidate facilities

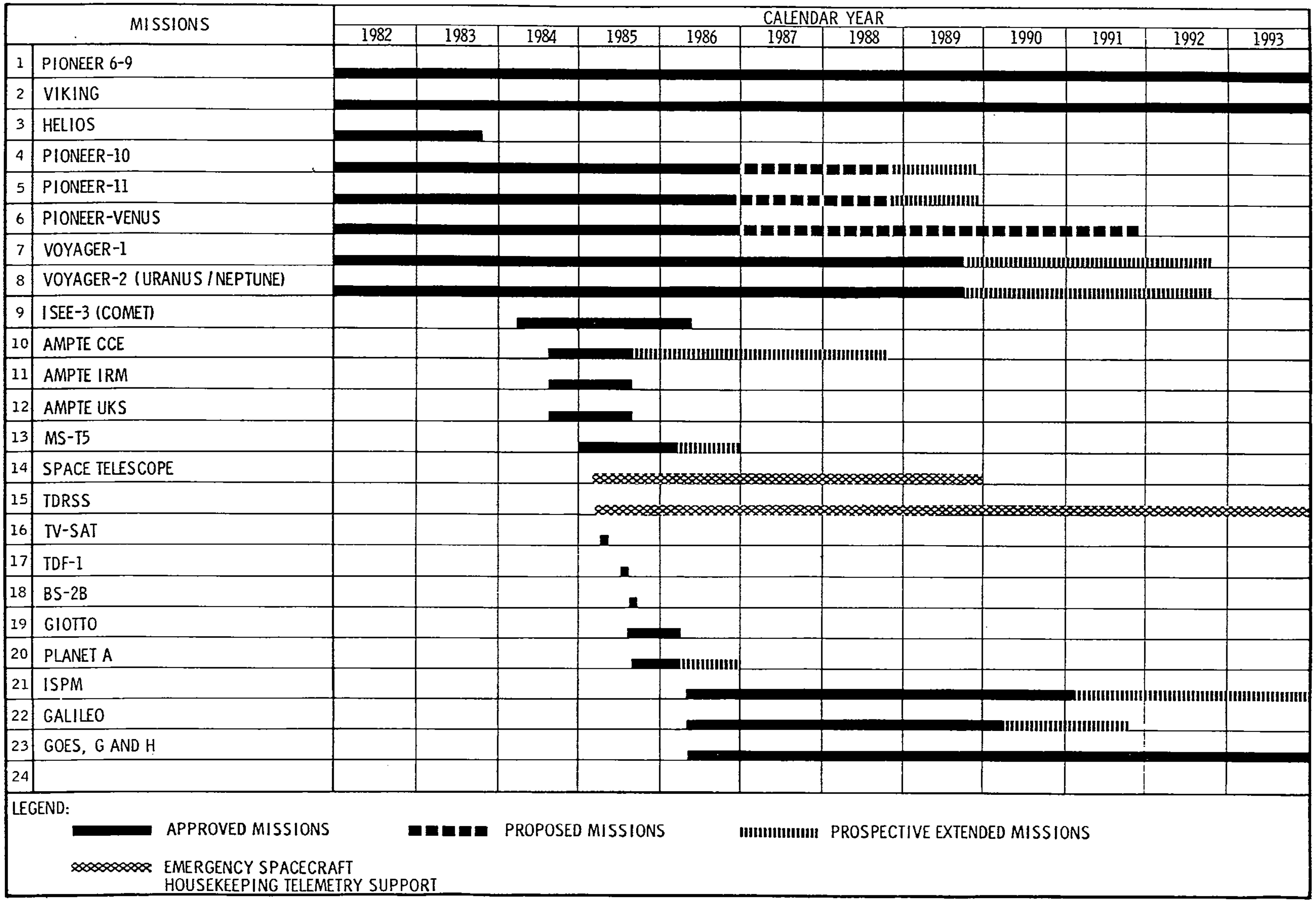


Fig. 4. Flight project support: mission set

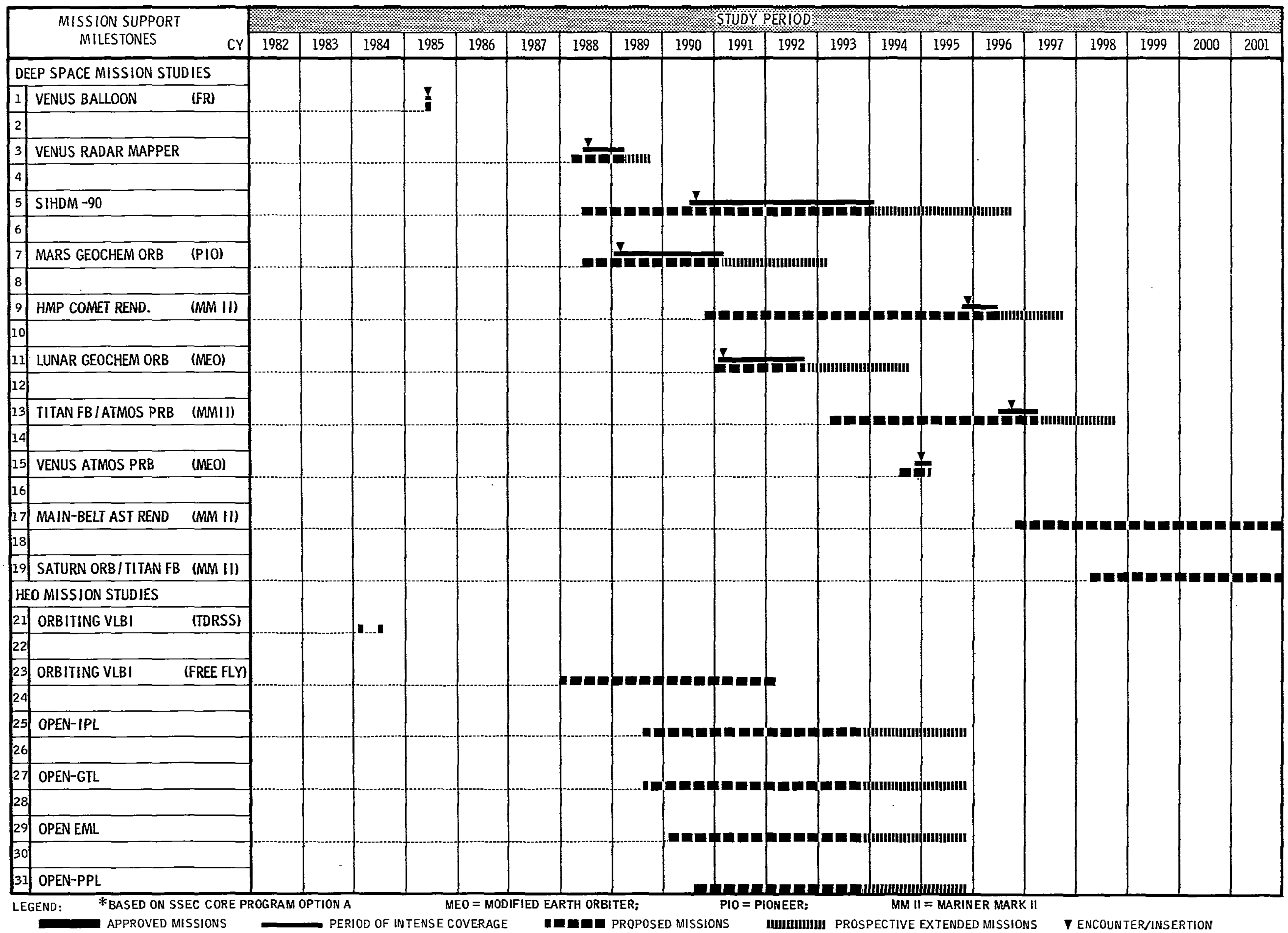


Fig. 5. Advanced planning missions: mission set

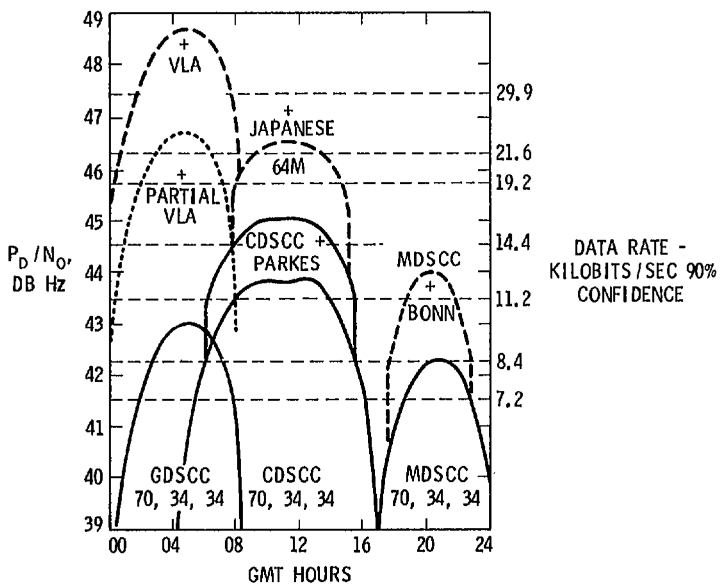


Fig. 6. Enhanced link performance at Uranus

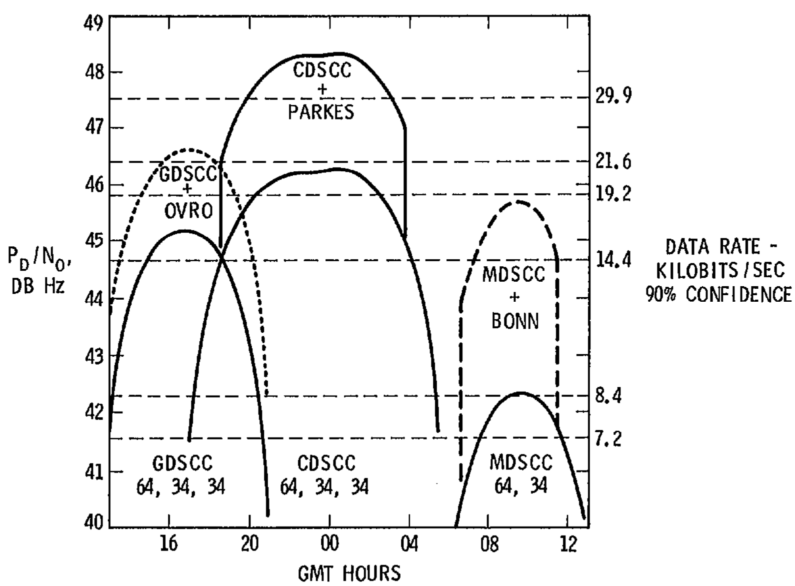


Fig. 7. Enhanced link performance at Neptune

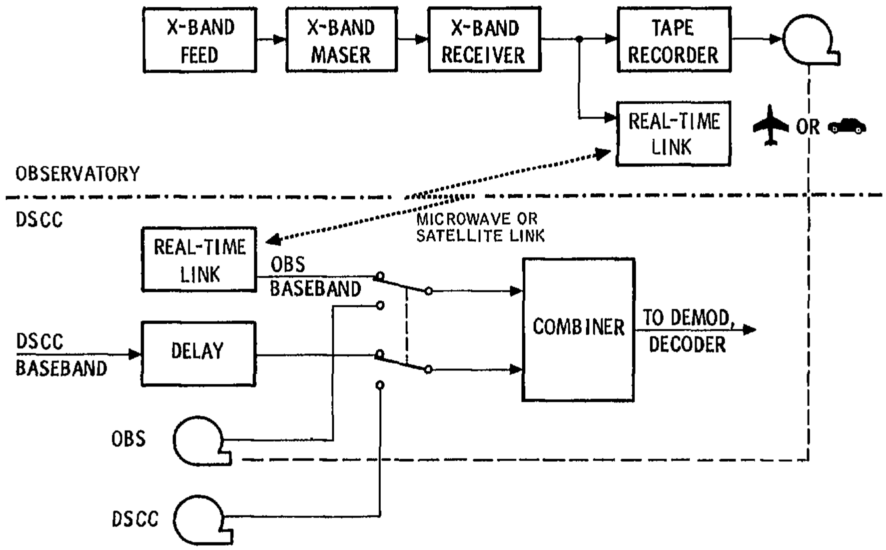


Fig. 8. Interagency arraying capability, functional block diagram

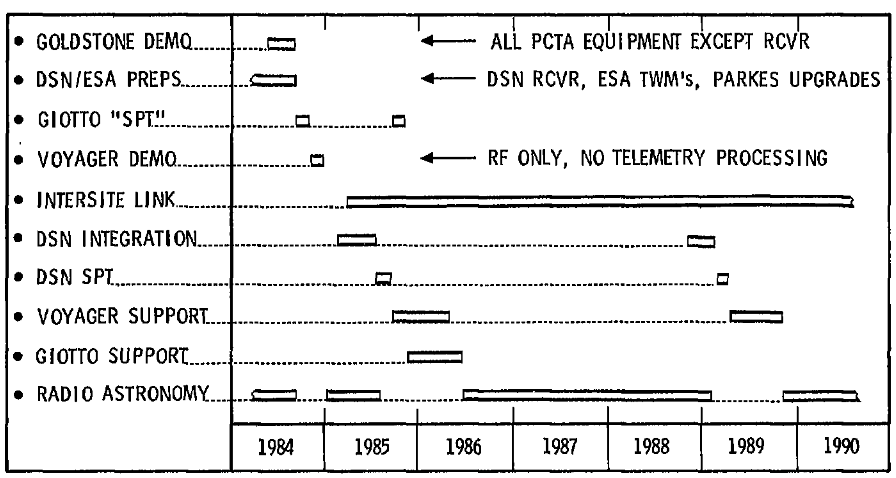


Fig. 9. Parkes on-site activity

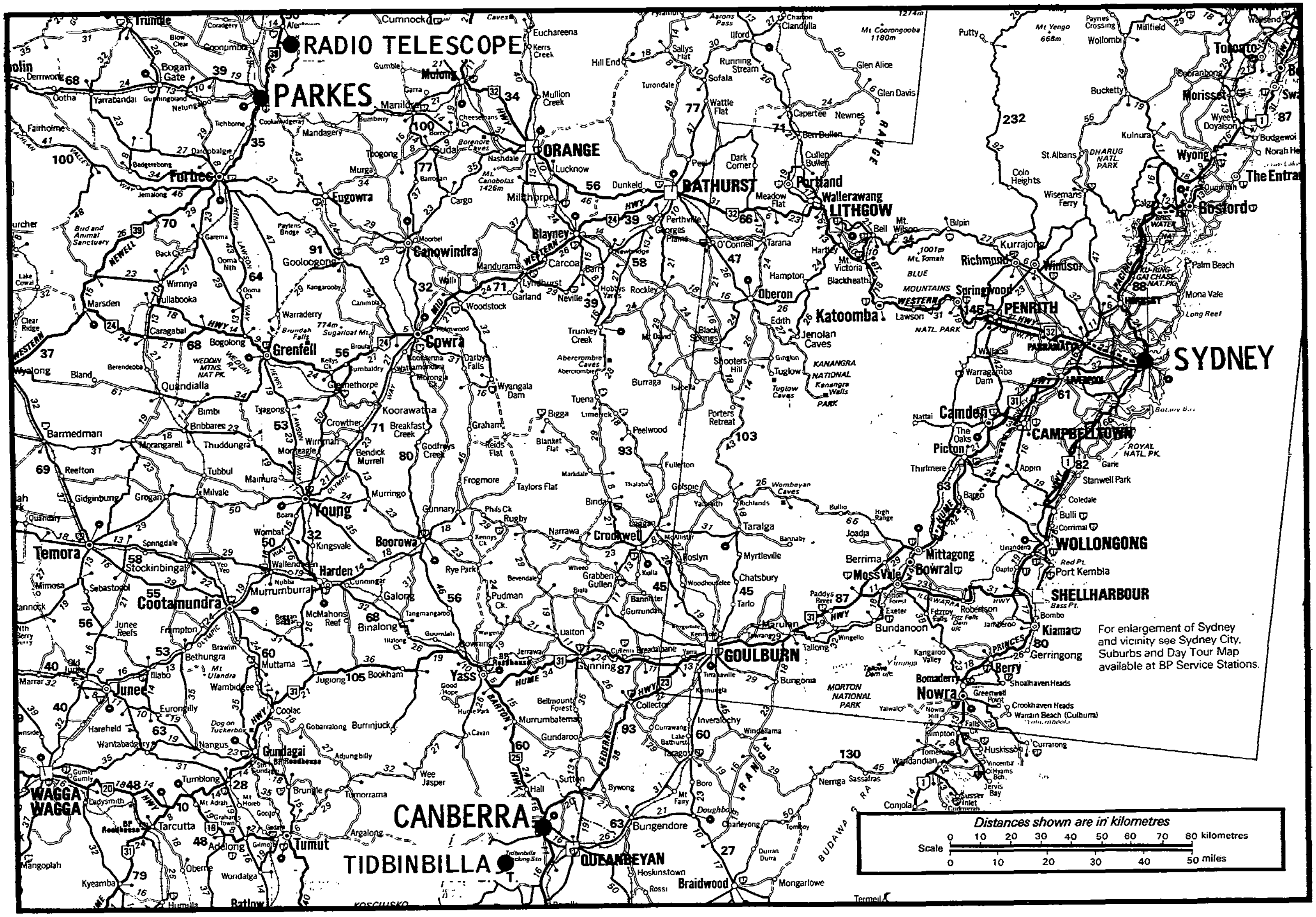


Fig. 10. Parkes-CDSCC telemetry array: site locations

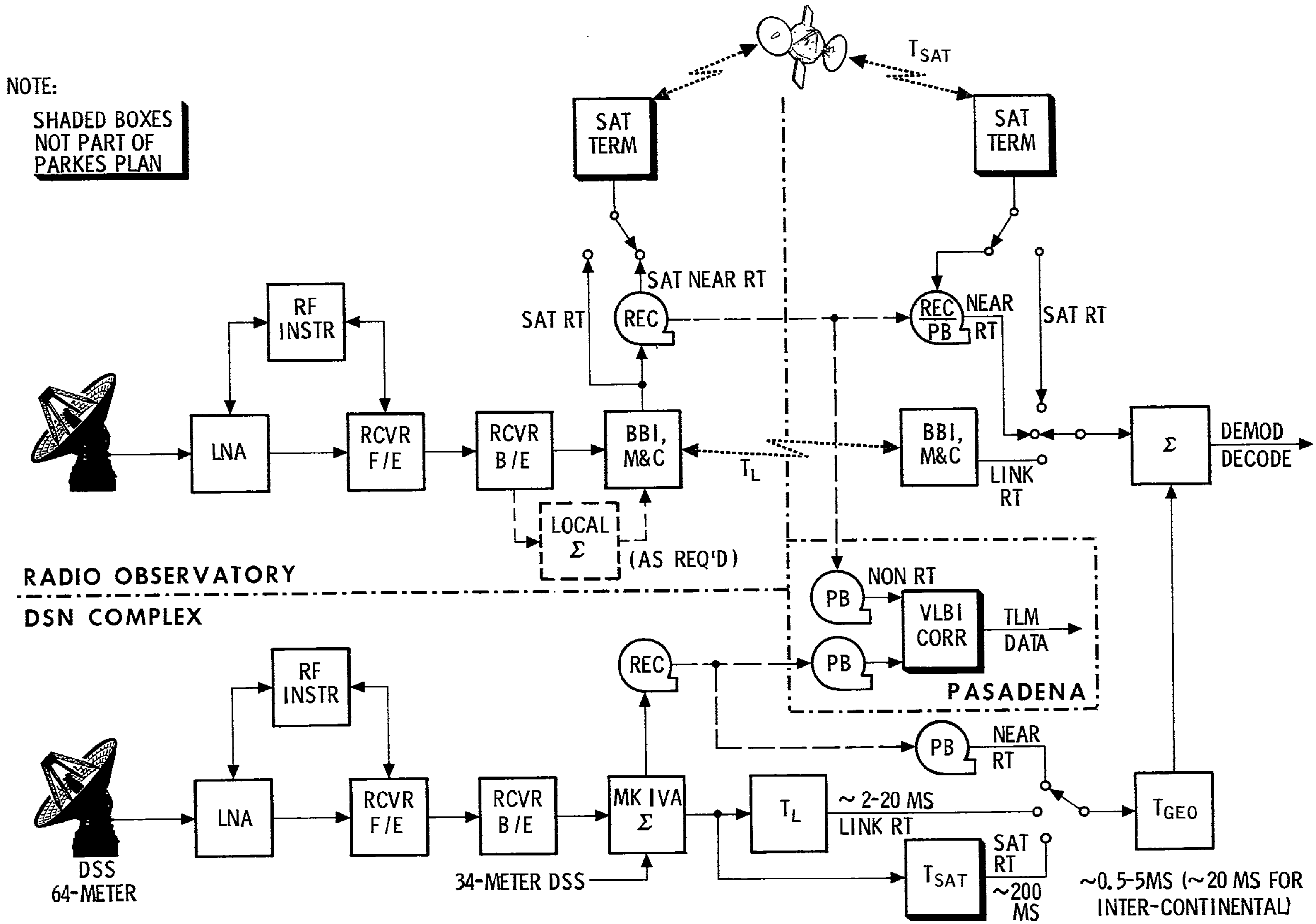


Fig. 11. Functional elements of array

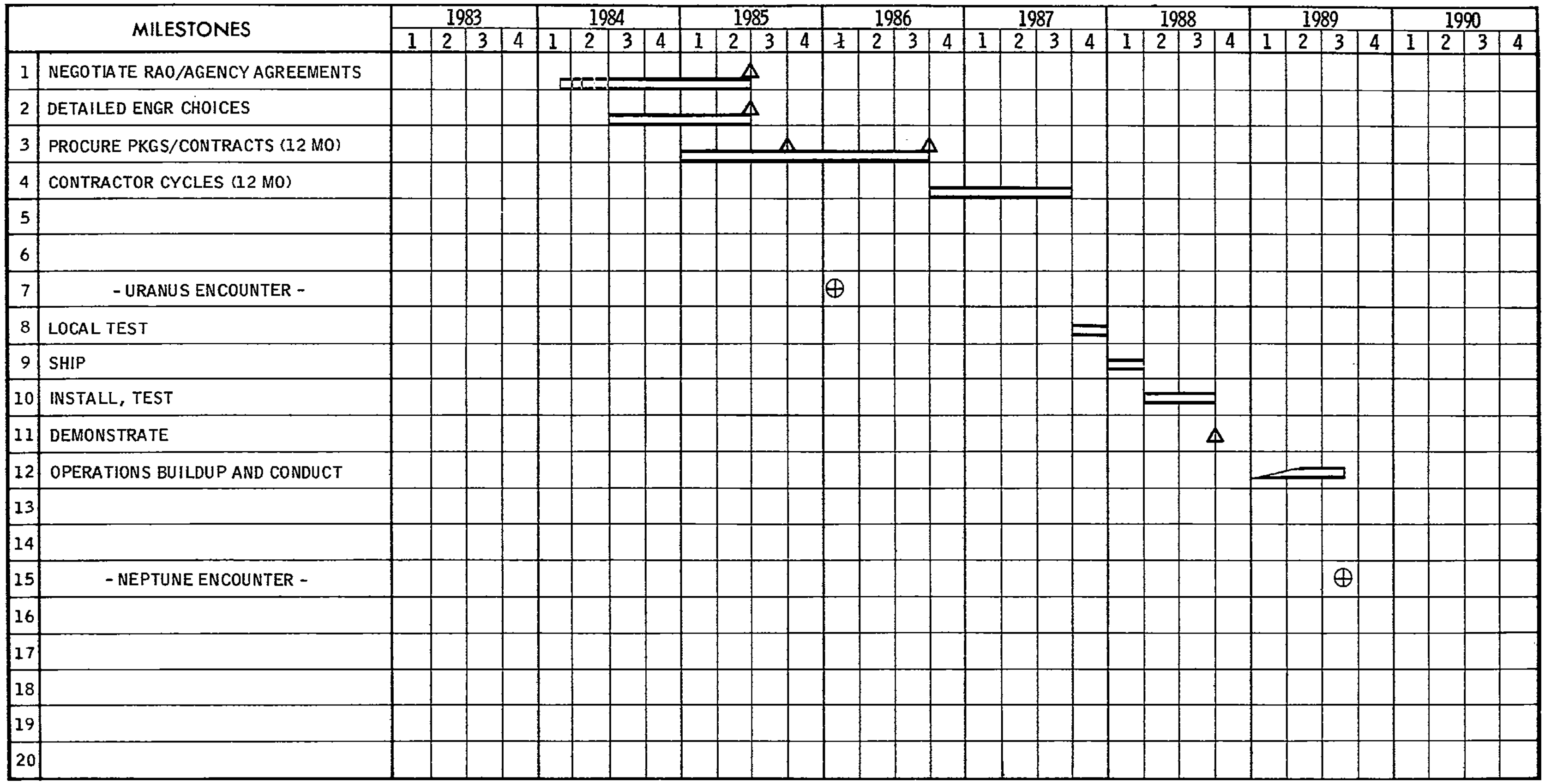


Fig. 12. Bonn/Japan 64-meter general schedule, late CY 1988 demos

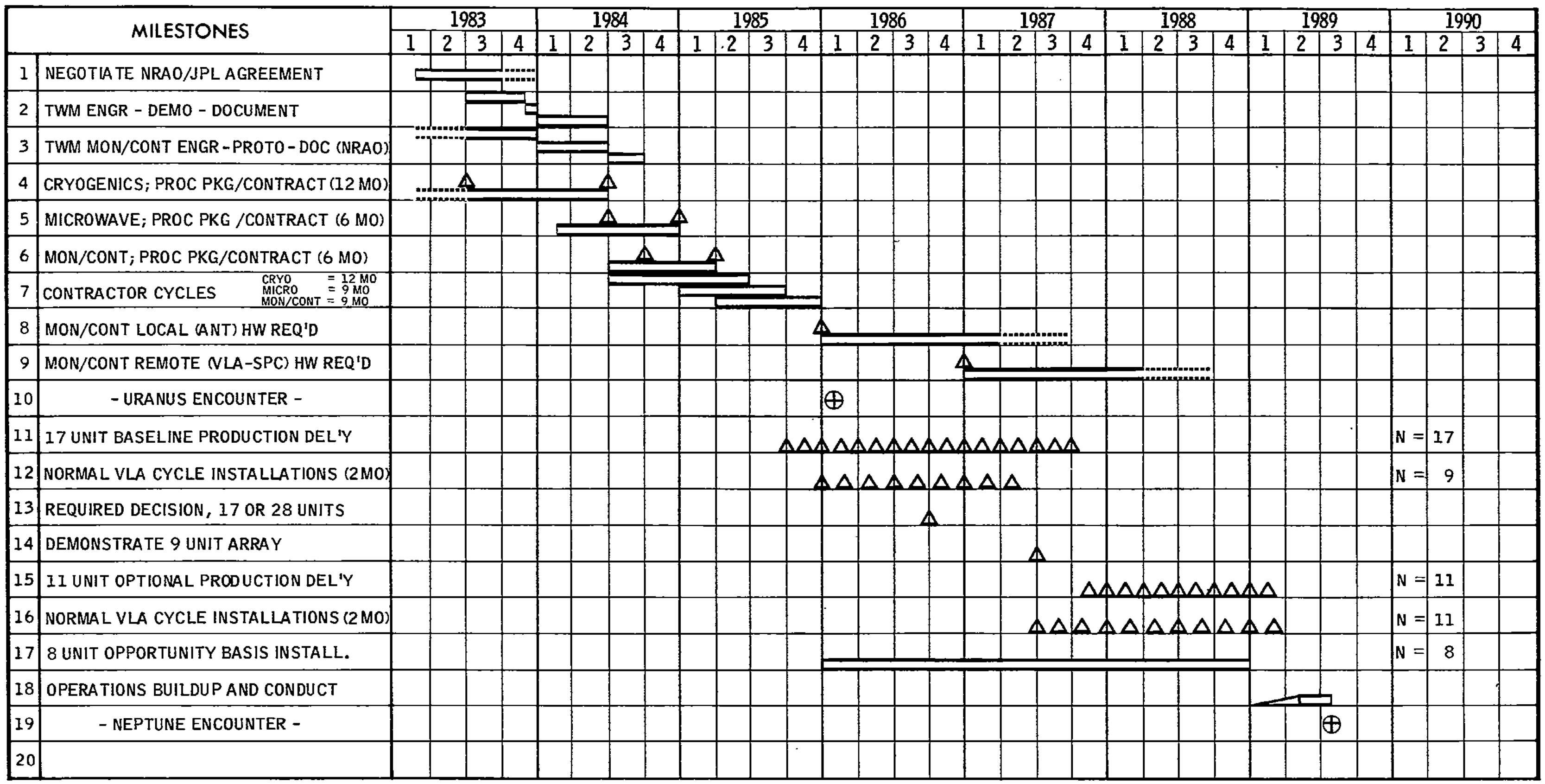


Fig. 13. Full capability schedule, NRAO/JPL for VLA

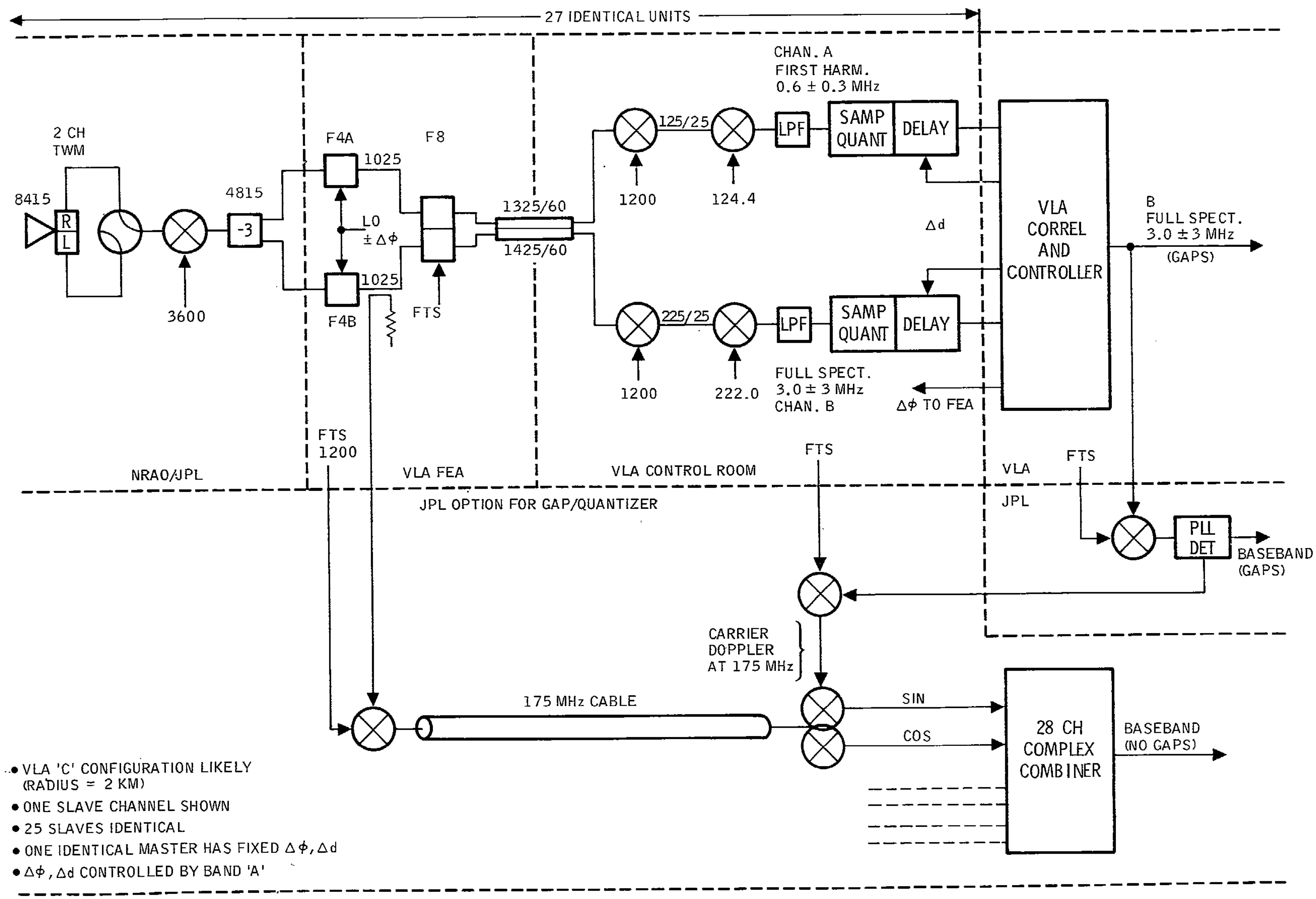
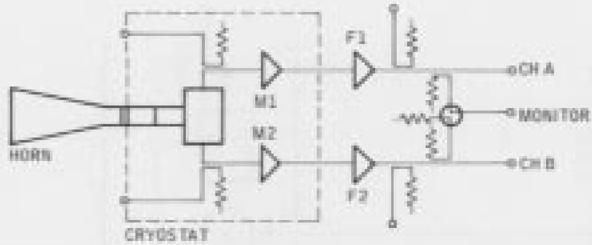


Fig. 14. General VLA configuration for Voyager support



- INTEGRAL TO 3 WATT CRYOSTAT:
  - TWO TWM STRUCTURES, EACH 1/2 OF DSN TYPE (M1, M2)
  - CIRCULAR POLARIZER AND ORTHOMODE
  - INPUT CALIBRATION DIRECTIONAL COUPLERS
- EXTERNAL TO CRYOSTAT:
  - TWO F.E.T. AMPLIFIERS (F1, F2)
  - OUTPUT CALIBRATION DIRECTIONAL COUPLERS

Fig. 15. Proposed Block III X-band dual-channel TWM NRAO/JPL

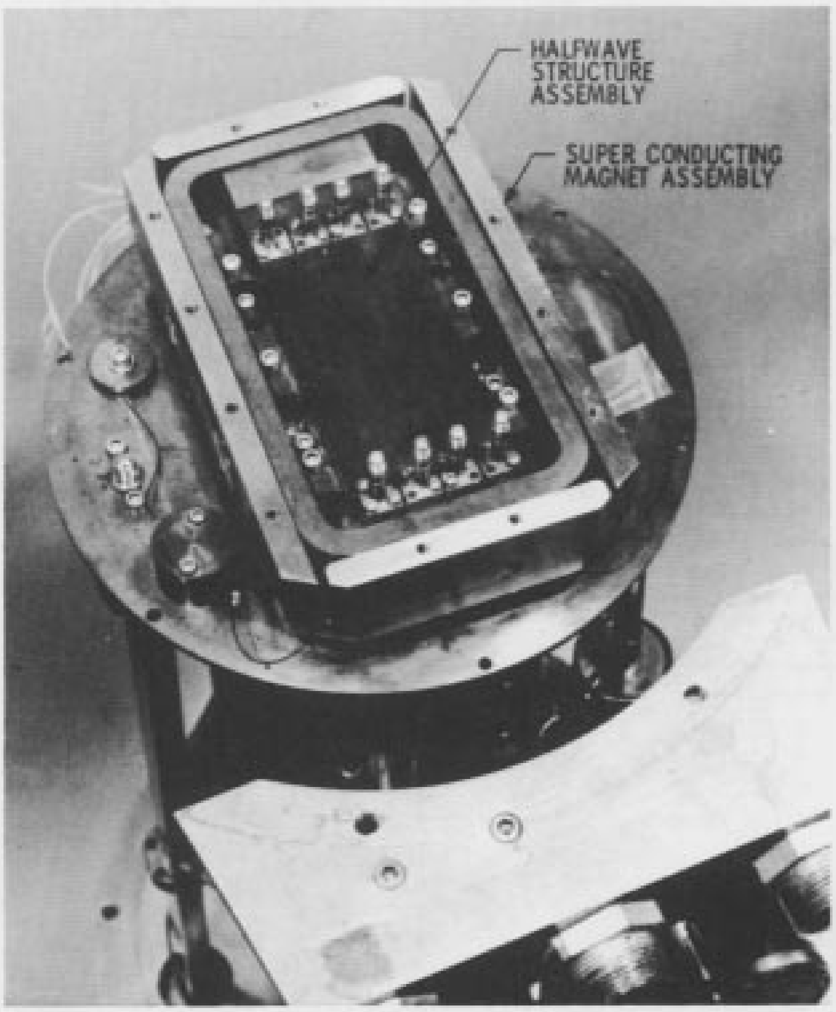


Fig. 16. X-band half-wave structure assembly mounted in superconducting magnet

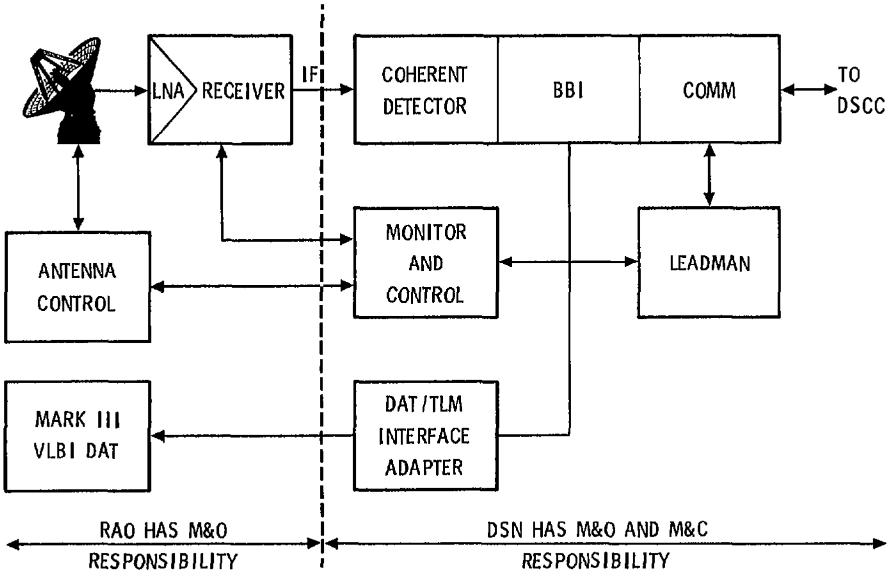


Fig. 17. Operations scenario: RAO basic functional block diagram

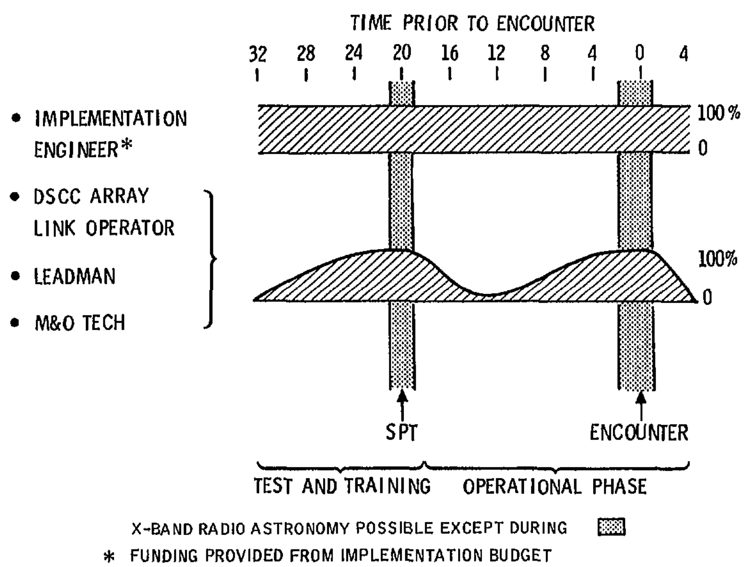


Fig. 18. Operations scenario: conceptual personnel deployment plan

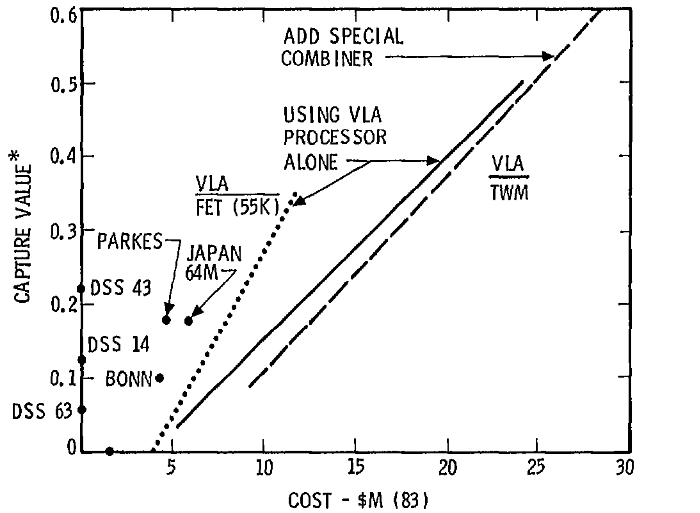


Fig. 19. Voyager signal capture vs cost

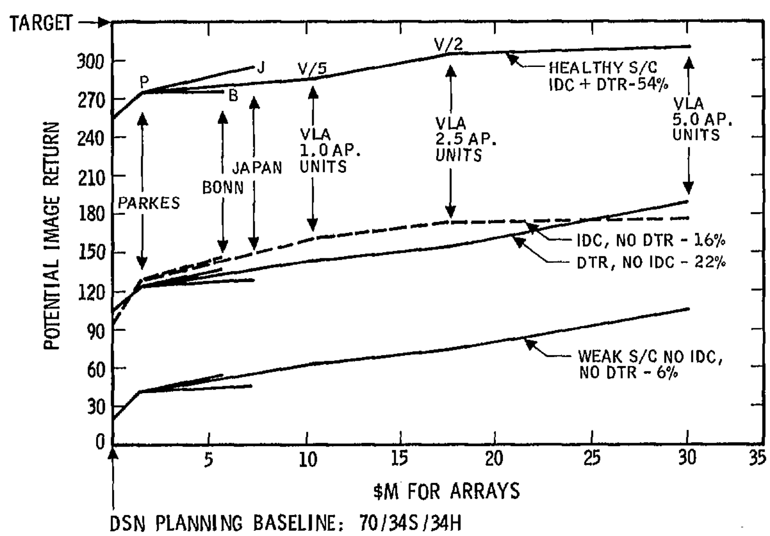


Fig. 20. Neptune imaging potential vs cost by spacecraft state at encounter