Implementation of Large Antennas for Deep Space Mission Support

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The large antennas of the DSN support reception of low-power telemetry signals from spacecraft (S/C), transmission of high power commands to S/C, and navigation of S/C by precision radio metric data. The specification and design of the antennas have been driven by the requirement to support those functions with high reliability. The number of antennas required in the DSN is determined by the number of S/C to be supported and their level of activity. A given size antenna aperture can be realized with a single element or by arraying smaller elements with the same total area. That approach can be applied to meeting many DSN requirements. There is a cost vs capability trade-off in arrayed vs single element designs. The operating microwave frequency is an important parameter for the antenna. Some of the communications and radio metric data functions are much improved at higher frequencies, e.g., X- vs S-Band. Current technology allows arraying for reception by antennas that are far apart. Thus, for example, major radio astronomy antennas can be arrayed with DSN antennas to increase reception capability during important scientific events, e.g., Voyager encounters with Uranus and Neptune. This article examines the specification, design, and development of DSN antennas in the context of the above considerations.

I. Introduction

This report describes the evolution of DSN large antenna capability for deep space mission support. The reasoning behind making particular design or configuration choices is given.

II. Deep Space Mission Generic Requirements

Deep space S/C missions require support of these principal technical functions:

High rate telemetry

Low rate telemetry

Routine command

Emergency command

Emergency telemetry/weak signal search

Generation of precision radio metric data

Sophisticated flight radio science experiment instrumentation

Some of the functions require support more often than others, but all of them must be supported at some time or other. Most of the functions put extraordinary requirements on the technical performance of the ground antennas.

In addition to deep space S/C missions, the DSN supports, or will support, other users whose antenna technical performance requirements are similar to those required for deep space mission support:

Planetary Radar

Radio Astronomy, especially VLBI, including earth orbital missions

The Search for Extraterrestrial Intelligence (SETI) Program

The mission support requirements have driven the DSN designs, as will be illustrated in following sections of this report.

III. Antenna Capacity to Meet Mission Support Requirements

The capacity, i.e., the number of separate antennas required, is determined by the number of individual supported missions and their required support level.

A. S/C Generic Requirements

All currently active deep space S/C require continuous two-way communications in high-activity phases, or daily downlink and frequent two-way passes in cruise phase. Thus, each high-activity S/C requires about 90 antenna passes per month (two or three times that when arraying is required), and each cruise S/C requires about 30 to 60 passes per month.

B. Support Capacity of DSN Antennas

A S/C support pass takes an average of 10 station hours, including pre- and post-pass calibrations (some passes are as short as two hours; some are as long as 13 hours). Thus, depending on the view periods of S/C supported, an antenna can support one to two passes per day (approximately 30 to 60 per month) plus allow time for station maintenance and repair. Based on empirical experience, DSN scheduling uses, for planning projections, an average capacity of 46 passes per antenna-month. For example, the average support capacity of the mid-80s (Voyager Uranus era) eight-antenna network of three 64-m and five 34-m antennas is about $8 \times 46 = 368$ passes per month; that of the proposed nine-antenna late-80s network (Voyager Neptune era) is about $9 \times 46 = 414$ passes per month.

C. Example of Antenna Support Capacity

As a simple illustration of network capacity vs requirements arithmetic, consider the following scenario, representative of DSN mission support in the late 80s prior to operational support of the SETI Program. There are eight missions supported – Pioneers 10, 11, 12; Voyagers 1, 2; Galileo; ISPM; VRM. Of these, assume one is in a high-activity phase and the other seven are in cruise. The total of passes required per month is approximately $1 \times 90 + 7 \times 45 = 405$ (an average number of 45 passes per month is used for the cruise missions, approximately satisfying their minimum requirements). The nine-antenna network has adequate average capacity (414 passes per month) to support the requirements; the eight-antenna network does not (368 passes per month).

D. The Mix of Antenna Sizes Required for Mission Support

All passes do not require the same ground antenna capability as assumed in the simple approach above; some support requires the largest antennas (64 m); other support is satisfied, and less expensively, by the 34-m antennas. There is the question of how many large vs how many smaller antennas should be provided.

The following considerations are involved. A deep space S/C is designed to provide maximum telemetry capability at its distant prime mission target. Also, at least to the distance when the S/C is near the target, both telemetry and command links must be supportable through the S/C low gain antenna that provides communications during S/C maneuvers or non-standard S/C behavior. At those times, in consonance with the mission telecommunications system design, the S/C will require support from the DSN's most capable antennas, transmitters, and receivers. At most other times and places, the S/C telemetry and command links have considerable excess of capability. Data rates required are typically much lower during S/C cruise periods, and at least during transit to the encounter target, the distance is less.

Also, the relative sizes of the large vs small antennas affect the ratio of the number of large vs small antennas that should be provided. For example, the Pioneer 11 S/C, which is departing from the solar system at the rate of about 2.5 A.U. per year, can be supported by a 34-m antenna until late 1986. After that time its support will be shifted to a 64-m antenna. If the smaller antenna were 26 m rather than 34 m, the shift to the 64-m antenna would have to occur by early 1984.

As another example, consider support of typical planetary orbiter missions. The distance between the Earth and a planet varies regularly. That produces a range of variation in communication link capability as shown below for the nearby planets:

Mercury	7 db
Venus	16 db
Mars	14 db
Jupiter	3 db
Saturn	2 db

If the S/C-ground communication system is designed to perform adequately at the time of maximum Earth-to-planet distance, it will have excess capability at other times. For example, if the link uses a 64-m antenna for support to maximum Earth-to-planet distance, an approximately 5 dB less capable 34-m antenna could support Venus and Mars orbiters more than half the time; a Mercury orbiter, for a brief time around inferior conjunction (7 - 5 = 2 dB margin at minimum distance); but Jupiter and Saturn orbiters, not at all.

By various means a quantitative estimate can be made of the relative amounts of support required from the large and small DSN antennas for typical deep space missions. One simple way is to examine the ensemble of technically laundered (i.e., S/C supported by the minimum satisfactory DSN capability) requirements established by the projects. We have done that for a sample of one-month periods – the month of August, for the years 1985 through 1993. The results show that, on average, one-third of the total passes requires support from the larger DSN antennas.

This concludes the discussion of the general planning approach to estimating the numbers of antennas and mix of sizes needed to meet projected support loading requirements. The next section addresses key design vs cost considerations that the DSN has encountered, and anticipates, in the evolution of its antenna facilities.

IV. Antenna Facility Design Approaches

A. The Beginning

The first DSN antennas for deep space mission support were 26 m in diameter with prime focus feeds. They were adapted from existing radio astronomy designs. They were used at L- and S-band frequencies to support low-yield encounter missions to Venus and Mars in the early 60s.

B. Development of the 64-m Antennas

Beginning in 1962, the DSN studied antenna designs to enable significant imaging yields from Mars. The studies concluded that the projected telemetry, command, and radio metric data requirements could best be met by apertures in the 50- to 80-m diameter range.

For significantly smaller aperture elements, used in an arrayed configuration, the costs rose steeply, dominated by electronics and O&M costs and their uncertainties; for significantly larger aperture elements the available design and construction technology was not considered adequate to support implementation with acceptable cost and performance risk. At that time the 64-m Parkes, Australia, radio astronomy antenna was the largest microwave antenna design that had been successfully executed.

The favored configuration from the many considered was a fully-steerable, symmetrical cassegrainian-fed, paraboloid operable at very low receiving system noise temperature. The prime operating frequency was S-band. Also, the studies argued that investment in DSN ground aperture provided cost effective communication increase compared with S/C capability increase. These arguments supported NASA's decision to design and implement the DSN 64-m subnet. It was started in 1963, finished in 1973.

C. More on Ground Antenna Diameter for Deep Space Mission Support

The subject of optimum antenna diameter vs cost addressed in the early studies has since been revisited several times by the DSN; it will come up several times in the present discussion. What follows will distill the proximate results of the studies.

The cost-optimum diameter depends on the technical requirements to be met by the antenna facilities. That is shown in Fig. 1, a plot of cost-optimum antenna element diameters to obtain an arbitrary increment of X- and S-band receiving, or transmitting or both, effective aperture. In Fig. 1, the horizontal axis is the approximate cost of the electronics and other equipment and facilities required with each aperture element to support the technical functions provided by the total aperture. The technical functions supported are also indicated on the horizontal axis; they are those listed in Section II of this paper. The vertical axis is the optimum diameter of the elements comprising the total aperture. Smaller elements are arrayed to make up the total aperture increment.

There is one conceptual uncertainty in Fig. 1. That involves arraying for transmission. Transmitter function costs are assumed the same for each element of an array, independent of the number, n, of elements. Actually, individual element transmitter costs decrease with n, while cost of radio frequency phase coordination of the individual elements increases with n. But the actual relationship is not known because the technology to phase relatively remote apertures for transmission is not yet in practice. The necessary practical technology can be, probably will be, available in five to ten years; meanwhile, the assumption used here is expected to be pretty close to the final outcome. At any rate, it is clear that for the DSN's purposes the only practical way in the next many years to achieve extremely high power transmission is with a single large aperture, so the issue is somewhat peripheral to the present discussion.

Return to Fig. 1, which, as stated, displays cost-optimum array element diameter vs the technical functions (or electronics cost) associated with each element of the array. The optimum diameter to provide all of the required DSN technical functions of Section II is in the range of 60 to 70 m, consistent with the early studies supporting the 64-m subnet implementation.

Another point should be made: achieving a cost optimum diameter to realize an aperture capability is important, but, within limits, it is neither critical nor totally unforgiving. Figure 2 displays the character of the cost vs diameter function – it gets steep (but nowadays predictably so) if the elements are much too small; and if the element size gets too large to be supported by mature design and construction technology, it gets simply unpredictable.

D. Consideration of Very Large Apertures

In the early 70s the DSN studied options to further increase communications capability for projected high-yield missions to more distant planets. By that time it was considered that antenna design and construction technology could support antennas for DSN use in the 100- to 130-m class with acceptable risk.

In the studies, it was assumed that such expensive antenna facilities, to be justifiable, would have to be operated continuously, either stand-alone as independent stations or as an array. Thus, operating costs for multiple antenna arrays increased relative to the model in the earlier study. Also, the complement of electronics being used on the 64-m DSN antennas was more extensive and costly than projected in the earlier study. As a result, cost-optimum element diameter increased to 120 to 130 m. However, the facilities were indeed very expensive.

At the time, it was believed by NASA that projections of the future level of activity in the planetary exploration program would not realize the need for continuous use of such a large capability. Therefore, the pursuit of 100- to 130-m class antennas and their justification rationale was put aside.

E. Consideration of Use of Higher Microwave Frequencies

Also, during the early 70s, the potential of X-band frequencies for providing increased telemetry capability using the existing DSN antenna facilities was studied. An experimental X-band planetary radar was first implemented on the 26-m Venus site antenna and later on the DSS 14 64-m antenna. The use of X-band produced the increased capability sought by the radar experimenters, but more importantly to the DSN, demonstrated the technical performance improvement and the operational viability of X-band for deep space mission support. X-band reception was initially implemented on the 64-m subnet to support Mariner Venus-Mercury 1973 and Viking Mars 1975 technology demonstration and radio science experiments.

It became clear that the increment of telemetry capability needed to support effective imaging data return from the middle planets, Jupiter and Saturn, could be achieved by use of X-band with relatively modest costs for changes to the S/C hardware and the DSN facilities.

F. Upgrade of 26-m S-Band to 34-m S/X-Band Subnet

To meet the commitment to Voyager for prime telemetry support at X-band, it was necessary to implement X-band on one subnet of smaller antennas. The combination of S- and X-band technical requirements could be met by an approximate 34-m diameter antenna. The approach selected was to increase the diameter and upgrade the performance of the DSS 12, 42, and 61 26-m subnet antennas. Although the upgrade to 34-m X-band capability of the original 26-m S-band design involved major modifications, it was still significantly less expensive than implementing new antennas:

Approach	Cost per Antenna (FY81 $M)
S/X 26–34-m Conversion	4.8
Implement New 34-m	5.6

The X-band capability was used with excellent results as the prime telemetry link by Voyager for Jupiter and Saturn encounter imaging and general science data. It will be used for Galileo, ISPM, and VRM missions.

G. Initial Study of 64-m Upgrade

In the mid 70s, a broad study was made of X-band telemetry performance upgrade options for the 64-m antennas. Of the menu, which included the currently proposed diameter increase to 70 m and high efficiency shaped surfaces, only the most economical and cost effective items were selected for implementation. These were improved X-band masers and microwave feed system components. Those upgrades provided a needed increment of performance for Voyager at Jupiter. The other options were set aside as not needed or affordable in the near term.

H. Early Array Applications

Technology for arraying the 64-m with the 34-m antennas was under development in the late 70s. Arraying was used experimentally at Goldstone to enhance the Voyager Jupiter encounter and as a committed capability at all three complexes for the Voyager Saturn encounter. Arraying of the antennas during the encounters provided a very useful additional 1 dB of capability, and because it used available DSN antenna facilities, it was relatively very inexpensive to implement.

I. Initial Considerations for Outer Planet Imaging Mission Support

1. **Background.** In the late 70s, the DSN considered the projected support requirements for the middle and late 80s. In principle the DSN had, or was developing, adequate technical performance to support all requirements of all seriously proposed inner and middle planet missions (i.e., Galileo, ISPM, VOIR, Halley's Comet). However, for outer planet high-yield imaging missions, it had no visible approach to providing the downlink telemetry capability that would be required.

Specifically, the extension of the Voyager 2 mission to encounter Uranus in 1986 was becoming a recognized possibility, but the DSN was without a seriously proposed means for supporting the encounter telemetry. The short fall was not 1 or 2 dB; more like 4 to 6 dB was needed to support the minimum imaging data rate at Uranus (6 dB is the increment of signal loss between Saturn and Uranus).

2. **The large advanced antenna station proposal.** The basic task of the design study team, which became known as the Large Advanced Antenna Station (LAAS) Project, was to identify the most cost effective solution to the problem of providing an X-band telemetry reception capability at least 5 dB greater than that of a DSN 64-m antenna. The LAAS Project considered economical antenna designs in the diameter range from 25 to 100 m and arrived at an array configuration of 34- to 40-m elements as the proper solution to the problem (cf. the region of Fig. 1 for single frequency telemetry reception, approximately $2M/element of electronics).

Three considerations developed in the early 80s that, taken together, are considered to have caused the LAAS pursuit to be set aside.

First, the planetary program was at least temporarily divested of high yield outer planet missions in the 90s that would have required the singular capability of the LAAS; the Voyager 2 at Uranus and possibly Neptune remained as the only likely mission requiring the capability for the next 20 years.

The second factor was emergence of the feasibility of implementing effective image data compression on board the Voyager 2 S/C to support Uranus encounter. The net effect of the data compression is an approximate 4 dB increase in imaging yield.

The third factor was the emergence and acceptance in principle, by the DSN and the Voyager Project, of the concept of using non-NASA-owned antenna facilities to augment the DSN's capability for encounter support.

The combination of S/C on-board data compression, arrayed use of the Parkes, Australia, Radio Astronomy Observatory 64-m antenna, and the addition of two arrayed DSN 34-m X-band high efficiency antennas can provide a satisfactory science data yield for Voyager at Uranus. That is the planned support configuration.

3. **The 34-m high efficiency antennas.** What resulted in the addition of the two new 34-m X-band antennas, just cited, started as a proposal for six by the MK IVA Project. The principal justification for the antennas was Voyager Uranus encounter support. This followed withdrawal of the more ambitious LAAS initiative, but the S/C data compression and non-NASA facility support paths were still perceived as quite uncertain.

The initial approach considered in-place modification to 34 m of existing NASA 26-m antennas, as was previously done in the S-X upgrade project. Configuration architecture studies by the MK IVA Project showed that it was clearly cost effective and technically acceptable to co-locate all antennas of a complex at a single site area. The added cost of relocating the antennas is quickly recovered. The MK IVA Project selected that configuration.

Cost and performance factors were compared for moving and upgrading the existing 26-m antennas vs implementing new 34-m antennas. The cost comparison is:

Approach	Cost per Antenna (FY81 $M)
Relocate and do S/X 26 to 34m Conversion	6.3
Implement New 34 m	5.6

Performance factors favored the new antennas. The MK IVA Project decided to implement the new antennas. Budgetary trade-offs coupled with growing faith that data compression and Parkes arraying would make it for Voyager Uranus resulted in reducing the number of antennas from six to two.

The above discussion has summarized the evolution to the present of DSN large antenna capability for deep space mission support. The next section presents some future developments that are currently being seriously studied and proposed for mission support in the late 80s and early 90s.

V. Proposed Evolution for The Voyager-Neptune Era

A. Background

The Voyager signals from Neptune will be 3.5 dB (more than a factor of 2) weaker than from Uranus. To achieve a comparable data yield, that deficit must be made up. There is no further potential improvement evident from the S/C; in fact, with the aging S/C, the opposite is true. Increasing the ground aperture is the only way evident to reduce the deficit.

Except for the Voyager 2 Neptune encounter, the DSN does not now perceive any S/C mission requirement for truly exceptional telemetry support throughout the mid 90s. Therefore, it is not considered reasonable for NASA to undertake making up the entire deficit by the necessary increase in DSN aperture. It would require more than doubling the present DSN aperture, an approximate $200M enterprise.

B. The Concept for 3+ dB X-Band Telemetry Ground Aperture Increase

The current DSN proposal to support Voyager 2 at Neptune is by limited augmentation of DSN antenna facilities combined with arraying of several major non-NASA antenna facilities at near-encounter. The approach is characterized below.

For Voyager Uranus encounter support, the DSN will apply three 64-m and five 34-m antennas providing 4.45 Aperture Units (Ap.U.)[1]; that will be augmented by 0.8 Ap.U. from the Parkes 64-m antenna for a total of 5.25 Ap.U.

For the Voyager Neptune encounter, the DSN proposes to increase the NASA-owned aperture to 6.45 Ap.U. by upgrading the existing 64-m antennas (adds 1.65 Ap.U.) and adding a new 34-m high efficiency antenna at Madrid (adds 0.35 Ap.U). Also, for three weeks around encounter, the DSN will be augmented by 4.47 Ap.U. provided by major non-NASA antenna facilities: one-half of the U.S. NRAO VLA, the Parkes 64-m and the Japanese 64-m antennas (the Bonn 100-m radiotelescope is also being considered).

[1] Aperture Unit = current X-band effective aperture of a DSN 64-m antenna @25 K system temperature.

For the close encounter period, the total aperture applied will be 6.45 Ap.U. (NASA/DSN) + 4.47 Ap.U. (non-NASA) for a total of 10.92 Ap.U. Thus, in the proposed approach, the ratio of aperture applied at Neptune vs Uranus encounters is 10.92/5.25 = 2.1 = +3.2 dB, which is close to the 3.5 dB deficit created by the greater distance to Neptune (30 AU) vs Uranus (20 AU). Just adding up apertures, as above, neglects the fact that southern aperture is more effective than northern for Voyager's southern declination, etc., but it pretty well characterizes the matter.

The proposed approach to Voyager Neptune support is currently considered to be viable and cost effective. There is minimal NASA investment in facilities and equipment that do not have evident application for NASA mission support after the Voyager use.

Use of the non-NASA facilities, which is a critical and fundamental part of the Neptune support proposal, is in the planning stages. No serious obstacles to the approach have been encountered thus far.

C. Applications of Proposed DSN Antenna Capability Increase to Other Missions

In addition to the application to the Voyager Neptune encounter, the 64-m upgrades and the Madrid new 34-m antenna are vital to providing the quantity of support passes projected to be required by high priority missions of the late 80s and early 90s.

At that time period, the increment of performance provided by the 64-m upgrade is particularly useful. It relieves projected network overload by reducing the need for multi-antenna arrayed support of individual high priority spacecraft and provides much improved support of the three very distant S/C (VGRs 1,2; PIO 10), which are cruising out of the solar system.

D. Considerations of Use of Higher Frequencies

The DSN is evaluating the potential benefits to communications and precision radio metric data from the use of Ka-band frequencies. There are frequency allocations at Ka-band for deep space research support.

The potential benefits of use of that band are attractive. In addition to providing more protected radio spectrum space, they include: reduced spacecraft communication system cost; radio metric data instrumentation finally free of propagation media charged particle induced errors; a significant increment in telemetry capability for future (circa year 2000) high-yield very distant missions.

To support development and demonstration of Ka-band system technology for deep space communications use, a new antenna and planetary radar capability are proposed for the Goldstone Venus Station. It is expected that it will be practical in the future to adapt the new 34-m high efficiency antennas and the upgraded 64-m antennas to use at Ka-band frequencies.

The history and projections of DSN antenna development described in this report are summarized in the time line of Fig. 3.

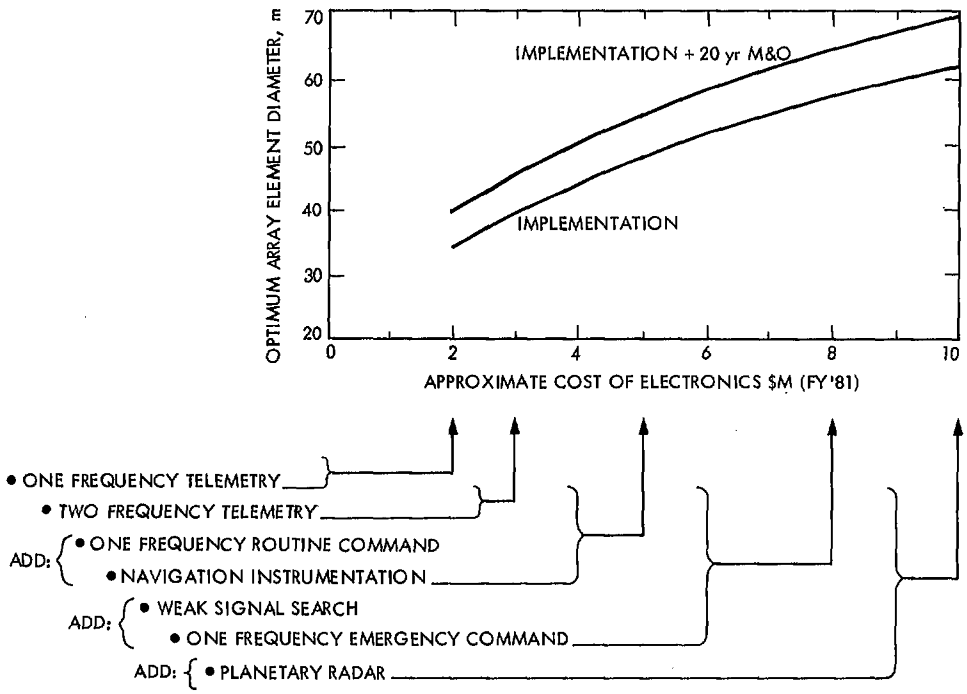

Fig. 1. Optimum element diameter vs technical functional capability of station

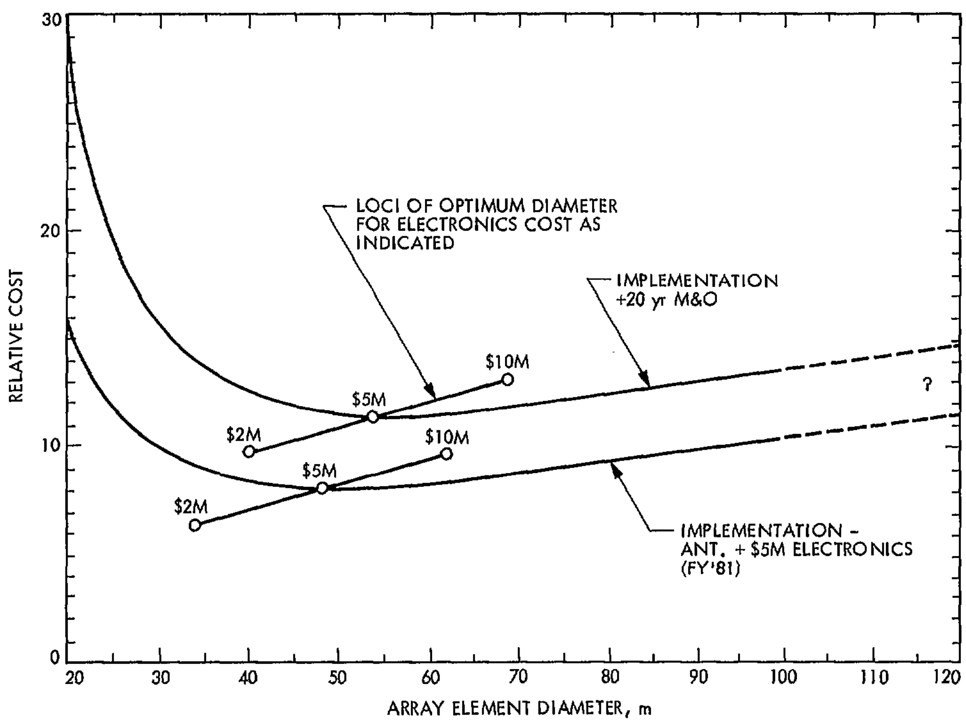

Fig. 2. Sample curve of cost vs diameter to add performance capability to DSN

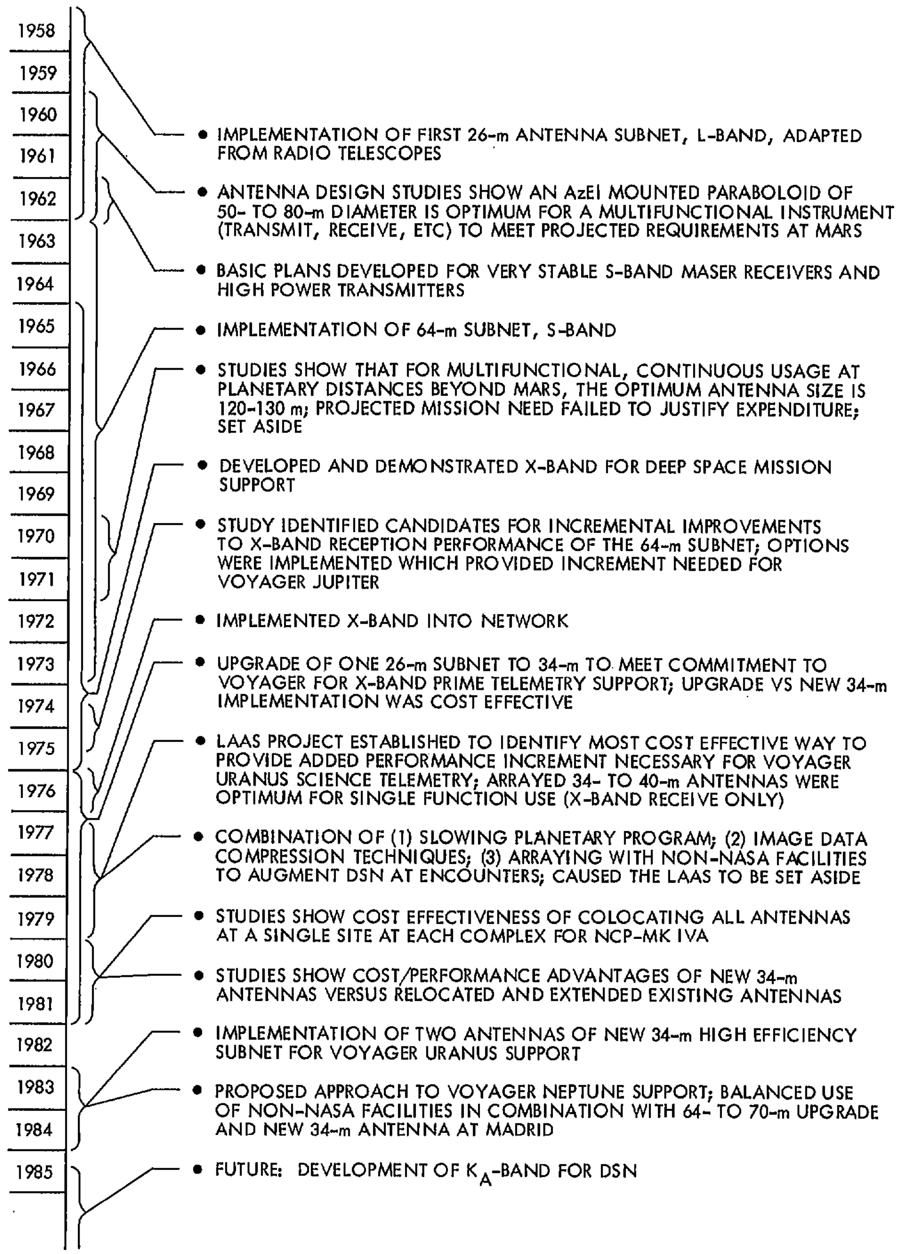

Fig. 3. Summary time line of DSN antenna implementations