Chapter 10

Future Development

This chapter provides a glimpse into the future development of array systems at JPL. Of particular interest is the ongoing effort within the DSN to build a prototype array having performance equivalent to several times that of a 70-m antenna. With proper funding, a system could be designed to expand and have an equivalent gain-to-noise-temperature ratio (G/T) of two orders of magnitude beyond the present 70-m antennas. Using such an aperture, data-intensive flight missions can achieve a significant increase in data return. Similar effort is being made by radio astronomers in building a Square Kilometer Array (SKA). Because of the synergy between this array and the DSN work, a description of the SKA development is provided below. Also discussed is possible development of an arrayed uplink capability that would increase the bandwidth in the forward link to the spacecraft. Such a capability is helpful in several scenarios: (1) establishing an uplink with a spacecraft that is in an emergency situation, (2) enabling a quick upload of special activities to a spacecraft when time is of the essence, and (3) supporting high-bandwidth communications with future astronauts. In addition, there is a potential need for the development of a software-based array system. Such a system offers unique advantages for mission scenarios in which it is important to extract, possibly post-pass, as much information as possible from a recorded signal.

The DSN is now at the crossroad of development. The systems in operation today trace their development back to the 1960s. The network started out with 26-m antennas, first operational in 1958. Over the course of time, antennas with increased aperture were added. The 34-m antenna subnet came, followed by the 64-m subnet in the early 1970s. In the late 1980s, the 64-m antennas were enlarged to 70-m. In the 1990s and early 2000s, additional 34-m antennas of beam-waveguide design were added to the network in response to an ever increasing demand for tracking resources. Along with the growth in aggregate aperture, the DSN also achieved improved performance via a steady reduction in the operating system noise temperature, realized by better design of the low-noise amplifiers and antenna feeds. The improvement in G/T relative to the cost of development, however, has now reached a plateau. Although aggregate aperture can be increased by building more and more 34-m and 70-m antennas, the cost of antenna construction remains high. In the early 2000s, the nominal cost of bringing a new 34-m antenna into operation—including antenna construction, uplink/downlink electronics, and integration testing—runs close to U.S. $30M. Because the individual antenna aperture is ultimately limited, there is strong motivation to maximize the performance capabilities of each antenna, e.g., by furnishing it with an amplifier of the lowest possible noise temperature. This drive for the best performance contributes to an overall increase in development and operations cost.

To significantly improve the G/T performance, a paradigm shift is necessary. Two possible paths of growth have been identified in the DSN strategy planning. One is to migrate to optical communications systems. The performance advantage is realized through higher operating frequency. The second approach is to stay in the radio frequency (RF) domain and achieve greater gain by arraying a large number of small antennas. The small aperture of each array element promises a low development cost. The savings come from the maturity of commercial technology in manufacturing small, low-cost antennas. Also leveraged are recent advances in monolithic microwave integrated circuit (MMIC) technology used in building low-noise amplifiers, downconverters, and other electronic components. With the economy of scale in manufacturing, the overall electronic cost, despite the greater number of elements deployed, is expected to be small compared to the cost of building monolithic large-aperture antennas. It is this type of large-scale RF array that is explored in more detail below.

10.1 The Square Kilometer Array

Over the past few years, radio astronomers have developed several system concepts for a Square Kilometer Array (SKA). The SKA implementation is an international collaborative effort, with team membership including the United States, Canada, several European Union countries, Australia, China, and India.

As the name implies, SKA is a system with a front-end that will have an effective aperture of a million square meters. With such an aperture, the system will enable astronomical and astrophysical research with two orders of magnitude improvement over current capability. Among the study interests, as defined by the SKA Science Working Group, are

1) The structure and evolution of galaxies
2) The evolution of large-scale structure in the universe

3) The life cycle of stars, from formation through death
4) The formation and evolution of planetary systems
5) The formation of life

To enable such studies, the SKA system requires a high detection sensitivity (a G/T of 20,000 m^2K^{-1}), a wide frequency coverage (150 MHz to 20 GHz), a large field of view (1 deg^2 at 1.4 GHz), and high resolution (0.1 arcseconds). The detection sensitivity enables the capturing of extremely faint signals. The low-end frequency coverage helps the detection of HI in the high red-shift region, corresponding to the epoch of re-ionization. The high-end frequency coverage permits the study of thermal sources, like dust in a proto-planetary disk or CO emission from high red-shift galaxies. The large instantaneous field of view allows for an efficient survey of both HI line and broadband continuum emission. Table 10-1 lists preliminary specifications for the SKA system [1].

Various systems utilizing different technologies are being proposed by different members of the SKA consortium. Some designs rely on parabolic antennas whose size varies from 10 m (as in the U.S. and Indian proposals)

Table 10-1. Specifications of the SKA system.

Parameter	Design Goal
Aperture-to-noise temperature ratio, A_{eff}/T_{sys}	20,000 m^2/K
Total frequency range	0.3–20 GHz
Imaging field of view	1 sq. degree at 1.4 GHz
Number of instantaneous pencil beams	100
Maximum primary beam separation	
Low frequency	100 deg
High frequency	1 deg at 1.4 GHz
Number of spatial pixels	10^8
Angular resolution	0.1 arcsec at 1.4 GHz
Surface brightness sensitivity	1 K at 0.1 arcsec (continuum)
Instantaneous bandwidth	$0.5 + \nu/5$ GHz
Number of spectral channels	10^4
Number of simultaneous frequency bands	2
Clean beam dynamic range	10^6
Polarization purity	–40 dB

to 200 m (as in the Canadian and Chinese proposals). The European proposal relies on phased array technology. The Australian team, on the other hand, is pushing the Luneburg lens concept. Detailed descriptions of each system are documented in [2]. Several prototype efforts at a smaller scale are under way to demonstrate the feasibility of each concept, e.g., the Allen Telescope Array (ATA) using parabolic antennas, and the Low Frequency Array (LOFAR) using phased array stations. Selection of the baseline SKA system is planned to occur in 2005.

10.2 The Allen Telescope Array

Among the many SKA prototype systems, the Allen Telescope Array (ATA), being built in Northern California by the University of California at Berkeley, is closest to the system being considered at JPL for the DSN. The ATA project aims at achieving an aggregate aperture of 100-m diameter from arraying 350 elements of 6.1-m dishes. The system is designed to operate over a frequency range of 500 MHz to 11.2 GHz. Figure 10-1 illustrates the main components in the ATA system [3].

Each antenna is equipped with offset-Gregorian optics and offers 56 percent antenna efficiency at 1 GHz. The feed is of log-periodic design, enabling a wide-bandwidth reception. The low-noise amplifier is cryogenically cooled to 60–80 K. The cooling system uses a Sterling cycle design, contains no contacting moving parts, and has an expected mean time between failures of one million hours! In the interest of minimizing the cost of development, operation, and maintenance, the antenna instrumentation is simplified as much

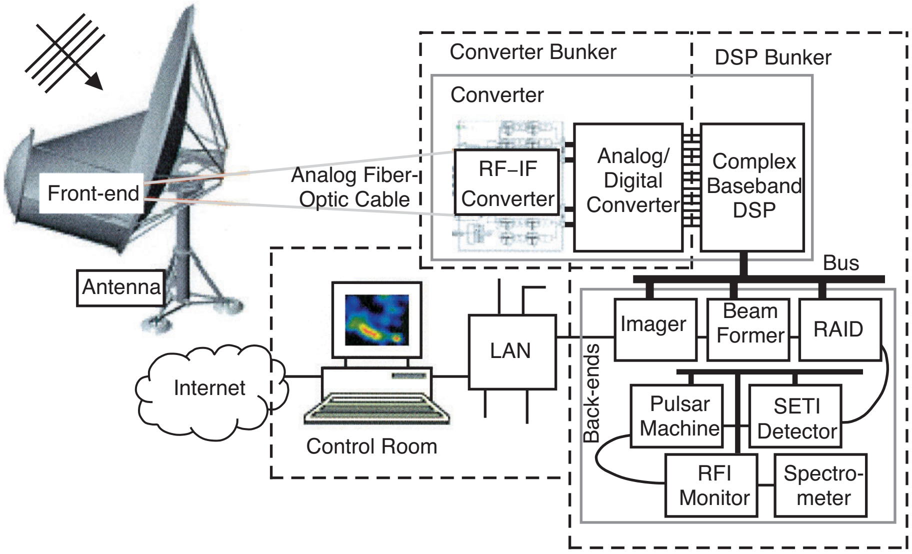

Fig. 10-1. Block diagram of the ATA system.

as possible. The received signals, after amplification, are routed to a central processing facility via analog fiber-optic links. All local oscillators and RF downconverters are housed in the central facility. This approach eliminates the need to distribute frequency and timing references of extreme stability to the antennas. For a system with many antenna elements, such a design can translate into significant cost savings. This scheme, however, relies on having high stability in the transporting fiber-optic network. Within the central processing facility, correlation is computed for all possible pairs of array elements. The ATA produces four simultaneous correlated beams, each with an instantaneous bandwidth of 100 MHz.

Since the overall frequency range of interest spans 11 GHz, and there are many commercial satellites currently operating within this band, radio frequency interference (RFI) demands special attention. The ATA design counteracts this problem by keeping track of the trajectories of these high-power satellites and adjusting the pointing of synthesized beams so that their nulls are in the direction of the interfering signals.

10.3 The DSN Large Array

A study is being conducted at JPL on the feasibility of deploying an array configuration consisting of hundreds of small antenna elements with sizes in the range of 6 m to 15 m in diameter. This configuration is similar to the SKA system proposed by the United States team. Justification for such a large aperture is based on the many different options that can be exercised by a planetary mission if such capacity exists. Figure 10-2 shows the data rate associated with many different options [4]. Data rates necessary to obtain images from planetary missions fall in the range of up to a few hundred kilobits per second (kb/s). For example, the current Mars Global Surveyor (MGS) mission uses approximately 30 kb/s. Scientific high-resolution synthetic radar and multi-spectral imaging data demand a much higher rate, typically in the 1–100 megabits per second (Mb/s) range. Such data cover many physical aspects of the object under study. Sampled data rates from deep-space probes (e.g., Magellan, Cassini) to near-Earth satellites (e.g., Terra with its onboard Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM), and Spaceborne Imaging Radar at C-band (SIR-C)) are shown in the figure. Ultimately, streaming video or high-definition television (HDTV) data at 1–100 Mb/s would promote a sense of tele-presence for mission operations. Such capability would also increase the level of public engagement in space exploration.

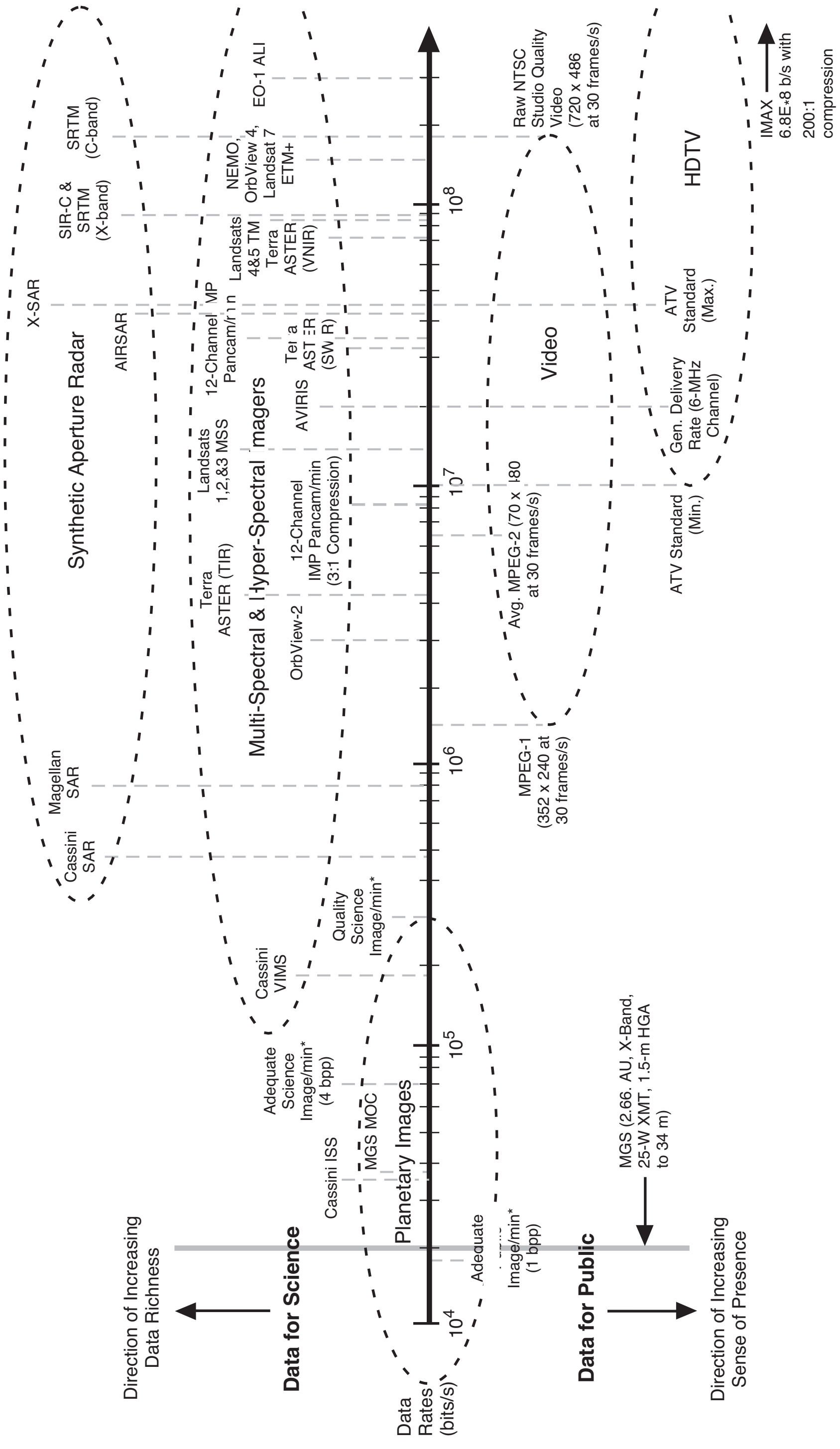

Fig. 10-2. Mission applications and associated data rate.

The DSN large array effort will begin with a prototype system that has an aggregate aperture of twice the 70-m antenna. The envisioned final system, to be completed over the next 10 to 15 years, may be 100 times as large, subject to funding availability. Despite the promise of low cost, there is still a high degree of uncertainty in such an implementation. Accordingly, the current prototype effort will help establish feasibility. From that experience, it is hoped the uncertainties in the life-cycle cost, from development to operation, can be narrowed. A better understanding of system performance, relative to flight mission support, will also be gained. DSN personnel will obtain the necessary experience with operation and maintenance of such a system. Preceding the prototype system will be the development of breadboard versions of a two- or three-element array using antennas similar to those of the ATA. The breadboard is intended for testing hardware and software components, developing integration and test procedures, and assessing signal processing and various monitor and control schemes.

The array is likely to be installed at multiple sites, probably in the Southwestern United States and at other overseas facilities. Such a deployment allows for a spatial diversity to counteract the impact of weather sensitivity at Ka-band (32 GHz). Large physical separation also allows for high-precision radio metric measurements using VLBI techniques such as delta differential one-way-ranging (delta DOR). Within a site, multiple sub-array configurations are possible. The system is being designed for operation at X-band (8.4 GHz) and Ka-band. Operation at the 37- to 38-GHz band, which is reserved for supporting future human deep-space exploration, is anticipated in the system design; however, equipment supporting such functions will not be implemented at this time due to the trade-off between implementation cost and need. Table 10-2 captures the essence of the current system specifications [5].

It is important to recognize that while there are synergy and commonality between systems that support radio-astronomy observations and those that support spacecraft communications, there are also significant differences. The differences translate to divergent design specifications for the two applications. One example is frequency coverage. Radio astronomy systems typically operate over a very wide spectrum to enable the study of different radio astronomical phenomena. In the case of the SKA project, this frequency coverage extends from 300 kHz to 20 GHz. In contrast, the signals from spacecraft are narrow-band sinusoidal, and they cluster within a narrow allocated frequency band of a few hundred MHz. Another difference is the layout of array elements. For imaging of a radio source, the log spiral configuration is deemed best in providing complete coverage in the spatial frequency plane. In spacecraft communications, it is more desirable for the site layout to produce a high-gain, narrow beam with small side lobes. Also, because of the importance of timely support to certain critical events in a mission’s lifetime, getting important data at the right time is urgently important so that mission objectives are not compromised. To support such operation, the system design must provide sufficient operational details to enable quick troubleshooting and replacement. This may imply a greater complexity in monitor and control design, and the operations facility may require higher levels of staffing. This translates to a preference for a more centrally located facility rather than dispersed remote facilities.

Figure 10-3 shows a conceptual design of such a system [6]. Received signals are captured at X-band and Ka-band, selectable for right- and left-circular polarization. The low-noise amplifiers are enclosed in a dewar to maximize the low-noise performance. The LNA expected performance, when cooled to 80 K, is about 15 K at X-band and 30 K at Ka-band. The

Table 10-2. Specifications of the DSN prototype system.

Parameter	Specifications
Processing function	Downlink only
Operating frequency range	8400–8620 MHz, S-band 31,800–32,300 MHz, Ka-band 37,000–38,000 MHz (goal, for future human exploration support)
Signal-processing channel bandwidth	>100 MHz
G/T_{sys}	>58.6 dB for all elevations, X-band >65.5 dB for all elevations, Ka-band
Tracking coverage	6–90 deg, elevation 0–360 deg, azimuth
Spectral purity	–65.7 dBc at 1 Hz offset from carrier –75.2 dBc at >100 Hz offset from carrier
Frequency stability	4.5×10^{-15} at 1000 s, X-band 1.4×10^{-15} at 1000 s, Ka-band
Gain stability	<0.2 dB variation across operating bandwidth
Polarization	Selectable TCP or LCP Simultaneous RCP and LCP (goal)
RCP/LCP isolation	>30 dB
Dynamic range	>55 dB
Number of synthesized beams	>2
Operability	Remotely operated from central control center Operable by a single operator Within 5%–7% of capital cost, per year

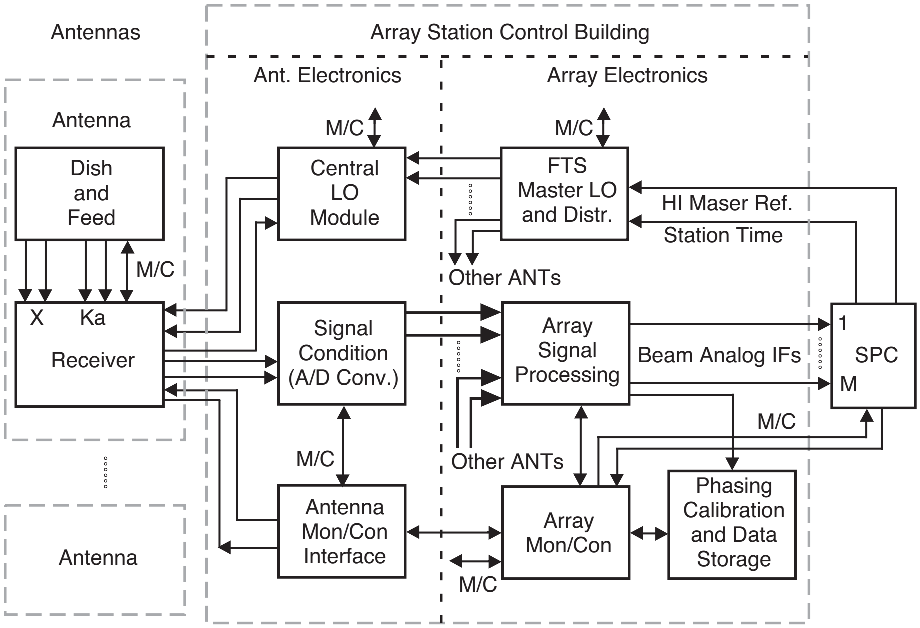

Fig. 10-3. Functional diagram of the DSN Large Array initiative.

RF signals are downconverted to the 0.5- to 1-GHz range and sent across the fiber-optic link to a central processing area. They are then digitized, filtered, and appropriately delayed to account for the difference in path delays. The signals then pass through a set of 1:16 beam splitters. A copy of each array element signal is correlated and then combined by one of the 16 beam formers that is part of the "backend" processing. Including 16 beam formers allows for expanded applications, more than enough to support the system requirements of 2 beams plus concurrent spacecraft tracking and quasar calibration. The beam splitter and beam former functions are implemented with FPGA chips. Figure 10-4 illustrates the proposed signal processing for arraying [7]. Once combined, the signal is routed to the existing DSN receiver and telemetry processor. The current DSN receiver was designed and built in the early 1990s. It supports a maximum data rate of 26 megasymbols per second (Msym/s). With the arrayed aperture, however, it is expected that higher data rates will be required in the support of future mission. Any such upgrade would have little impact on the array front-end because the interface between the two portions of the system is well defined and has minimum coupling

In addition to technical performance, the array design must also achieve maximum operability and minimum life-cycle cost. To optimize the solution against these constraints, careful consideration must be given to the overall system design. A few design aspects of interest are highlighted below.

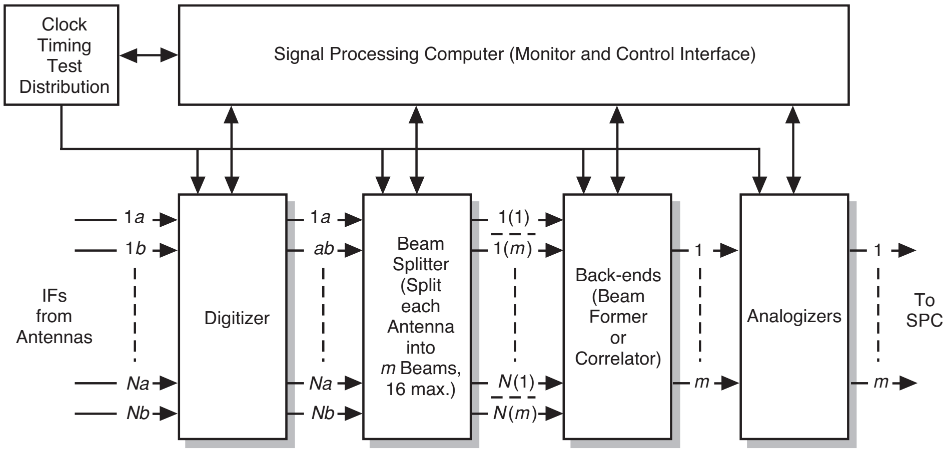

Fig. 10-4. Proposed scheme for signal processing for the DSN Large Array.

10.3.1 Correlation

The challenge is in performing the correlation on very faint received signals. In the interest of low electronic cost, it is expected that the system noise temperature at each array element will be higher than that achieved at the current 34-m and 70-m antennas. Coupled with the smaller aperture, the resulting SNR at each array element may be quite low. For example, to synthesize an equivalent 70-m aperture from a set of 12-m array elements, the signal received at each array element is at least 15 dB lower than at the combined aperture. Assuming a combined symbol SNR of –5 dB-Hz, the signal level at each array element would be less than –20 dB-Hz. For an array configuration to synthesize an aperture greater than a 70-m antenna, the input SNR at each array element becomes progressively smaller. Since the atmospheric fluctuation places a constraint on how long the signal can be coherently integrated, the task of correlating many inputs at an extremely low SNR is challenging. It is likely that techniques such as "Sumple," described in Chapter 8, will be needed.

For a spacecraft signal that is too weak for correlation, a calibration method using other targets, such as natural radio sources, will be required. A fraction of the array elements can be devoted to tracking the calibration source. The relative delays among different signal paths caused by the Earth atmosphere then can be transferred to those antennas that are concurrently tracking the spacecraft.

10.3.2 Monitor and Control

As the array size grows, the number of elements to be monitored and controlled increases accordingly. The ability to detect a problem, to properly identify the element causing the problem, and to carry out corrective action is essential to making the array operational complexity transparent to operators. Another consideration is the amount of information to be monitored. Finding the right level of monitoring to enable the maintenance personnel to promptly restore system service is essential. The larger the size of the least replaceable elements, the simpler is the structure of the equipment monitor. However, the cost for replaceable hardware would be higher, as well as the time for repair of the replaceable element because of its increased complexity. Clearly, an optimal structure depends on the way a logical function is mapped onto hardware and the cost of a replacement element. If a logical function is distributed over several components, individual monitoring will be needed. If the hardware cost is low, a monitor on go/no-go status and an order of replacement is all that is needed, rather than having to monitor individual components within a replaceable element.

10.3.3 Signal Distribution

Within an array site, one has to be concerned with preserving the integrity of the frequency and timing references distributed to different array elements. The design choice can be modeled after the ATA by keeping the local oscillators at a central location, rather than at individual array antennas. The constraint is that the fiber-optic system that routes the RF signal to the central facility must operate at Ka-band. Today commercial fiber-optic transmission systems are not readily available at such frequencies. Thus, a trade has to be made concerning whether to push for a technology advance in a few years or to rely on the distribution of local oscillators to the antennas.

Synchronization of the timing reference between two array sites is also required to enable inter-site arraying. While various technical solutions exist for small-scale distribution networks, a design choice that minimizes the near-term implementation cost while offering maximum future scalability requires careful attention.

10.3.4 Maintenance

A large array involves a very large amount of electronics. This equipment, due to its heavy capital investment, is expected to operate over 20-plus years. Over this period, many electronic components will become obsolete, making it hard to build replacement units in later years. It is critical to maintain a sufficient amount of spares for hardware replacement throughout the system operating life cycle. The hardware design, with its choice of parts, technology, etc., has to account for this maintenance consideration from the very beginning.

10.3.5 Data Routing

Today, the bandwidth of wide-area networks connecting the project users to DSN tracking stations is restricted to a few Mb/s. The connection relies on dedicated leased lines from telecommunication vendors. While such lines offer dedicated bandwidth and relatively high security, they are expensive. Also, such an approach will need a major upgrade for support of future array operations. Subscribing to more leased lines for the required high-rate interconnections among many array sites is not likely to be a cost-effective solution. The new design will need to consider other bandwidth-sharing infrastructure, such as the internet. Of course, desired features in data security and latency will have to be addressed as well.

10.4 The Uplink Array

In the current plan, the DSN array design effort only targets downlink processing. Support for uplink functions is being left to the existing 34-m and 70-m antennas. The lack of uplink capability within the array system poses several disadvantages, namely:

1) Dependency on the 34-m and 70-m antenna operation continues into the foreseeable future.
2) Spatial diversity against Ka-band weather is compromised. It is expected that, not too far into the future, deep-space mission operations will be moving toward full Ka-band uplink and downlink. Given that possibility, having command functionality at each array site is important to mitigate the weather impact. (Note that most present missions operate at X-band. New missions, such as Kepler, are beginning to include Ka-band downlink. However, X-band uplink and X-band downlink in an emergency situation are still expected in the near future.)
3) Two-way ranging measurements, wherein the transmitting and receiving stations are co-located, cannot be conducted, either at X-band or Ka-band. Two-way configuration offers better measurement accuracy than does three-way.
4) There is no extension to the equivalent isotrophic radiative power (EIRP) beyond the current capability. Such an extended capability is highly desirable in certain special operations, such as searching for a missing spacecraft. Even with regular tracking of a faraway spacecraft, such as Pioneer, a high-power uplink (100 kW at a 70-m antenna) is typically required.

It is clearly desirable that the uplink function be incorporated into the array system. However, if only one array element were to serve as the transmitting antenna for the entire array, its small aperture would require a high transmitting power to achieve the required EIRP received at the spacecraft. The required power increase is proportional to the ratio of the effective arrayed aperture and the physical aperture of a single element. For example, to maintain an equivalent radiating power of 20 kW on the 70-m antenna, 680 kW is needed on the 12-m antenna. Such a high-power transmitter poses a problem. Not only would it be more complex to build, it also would be more costly to operate. In addition, there is also the radiation safety issue. The radiating power in the near field would far exceed the 10 mW/cm^2 recommended safety level for radiation exposure at microwave frequencies for the operations crew on the ground and for any aircraft that might travel inside the air corridor of the beam.

Given these considerations, an arrayed uplink is deemed necessary in any final system. However, before the design can be accomplished, a solution must be obtained to the transmitter alignment problem. Since a spacecraft does not have the means to align the signals received from different transmitting antennas, the phasing for uplink signals must be done on the ground. Such alignment needs to account for instabilities caused by the uplink electronics as well as that caused by tropospheric variation, as described below.

10.4.1 Electronic Stability

The integration time required for a ranging measurement in a deep-space environment can be as long as 1000 seconds. The uplink electronics must be sufficiently stable over this time frame. This stability can be achieved with proper design of the electronic components or with proper compensation for the measured drift.

10.4.2 Tropospheric Variation

Two approaches can be used to compensate for tropospheric variation. The first is to use the measured variation obtained from downlink processing. Since it is the Earth's tropospheric effect that needs to be removed, as long as the latency in data processing is smaller than a typical 20-second time constant of tropospheric variation, the transfer of the correction factor from downlink to uplink is valid. Obviously, this option is constrained by the availability of a downlink signal. It also introduces an acquisition delay on the uplink path.

Another approach is to bounce a radar signal to a near-Earth orbital target and determine the tropospheric variation from the received echo. Such a scheme is described in [8] for two 34-meter antennas operated at 5-kW peak power. The drawback of this scheme, compared to the use of downlink information, is the requirement for additional radar signal processing equipment. It also requires the calibration target to be in the proximity of the spacecraft.

10.5 Software Combiner

A case can also be made for developing a software combiner to be part of the array. Such a system was developed for the Galileo Mission; however, its capability was limited to low data rate, up to 1 ksym/s [9]. A high-rate software combiner, in the Mars range, would be desirable. Despite the support data rate being lower than the hardware-based real-time array system discussed earlier, the software combiner can offer certain advantages. For example,

1) Being software based, it can be modified to include new capability and new algorithms rather quickly.
2) In the context of special planetary events, e.g., encounter, entry/descent/landing, wherein signal level is often a limiting factor, a software combiner can boost the chance of recovering precious information from recorded data at a later time. As an example, for the upcoming 2004 landing of the Mars Exploration Rovers (MERs), data recording at all 70-m and 34-m antennas within a tracking complex is being planned with the intention that they can be combined in post-pass to enhance signal detection.
3) In the context of the DSN large array effort, it can be used to combine signals from various array sites. Since the data can be transmitted via internet-type packets, it can relieve the need for having a point-to-point fiber-optic link between sites that would be required by a hardware-based system.

10.6 Final Remarks

In summary, there is clearly much activity with significant promise in the area of array development, both within the DSN and internationally under the SKA charter. Ongoing effort is being put into building prototype systems. Their presence will eventually lead to a larger version of a telemetry array with two orders of magnitude improvement over currently available aperture. The higher communication bandwidth offered by such a system will significantly increase tele-science and tele-presence in space exploration.

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