The Deep Space Network Advanced Systems Program

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ABSTRACT
The deep space network (DSN)—with its three complexes in Goldstone, California, Madrid, Spain, and Canberra, Australia—provides the resources to track and communicate with planetary and deep space missions. Each complex consists of an array of capabilities for tracking probes almost anywhere in the solar system. A number of innovative hardware, software and procedural tools are used for day-to-day operations at DSN complexes as well as at the network control at the Jet Propulsion Laboratory (JPL). Systems and technologies employed by the network include large-aperture antennas (34-m and 70-m), cryogenically cooled receivers, high-power transmitters, stable frequency and timing distribution assemblies, modulation and coding schemes, spacecraft transponders, radiometric tracking techniques, etc. The DSN operates at multiple frequencies, including the 2-GHz band, the 7/8-GHz band, and the 32/34-GHz band.

To meet the ever-increasing resource demands of NASA missions and its international clients, the DSN continues to evolve via investments in relevant technologies and advanced systems. These investments in communications and tracking studies and developments are managed at JPL through the Advanced Systems Program, which enables DSN evolution and long-term innovation. This paper introduces current Advanced Systems Program tasks[1], discusses recent accomplishments, and addresses product infusion. Current program focus is on increasing the downlink and uplink bit rate capabilities by factors of 10 and 1000, respectively, improving radiometric accuracy by at least a factor of 2, and reducing operational complexity and cost. These goals are achieved via investments in a new software-radio transponder, a new low-mass high stability space clock, new coding techniques, novel approaches in radiometric measurements, and more.

[1] There is a major effort underway to introduce optical communications capability into the DSN by developing a flight optical transponder. This effort is managed via a separate technology development program, and hence will not be addressed here.

1. Introduction

NASA's Deep Space Network (DSN) is the principal medium for passing information between the Earth and spacecraft operating beyond geocentric orbit. In addition, the DSN's careful measurement of link parameters provides a key component of navigation and radio science for these missions. As such, the DSN has, since its inception about 45 years ago, enabled communication and navigation for all of NASA's space endeavors beyond geocentric orbit, including all missions that travel through the solar system engaged in planetary science, astrophysics, and heliophysics.

The DSN comprises three Deep Space Communication Complexes, one station each in California, Spain, and Australia. Deep space ecliptic-plane missions are always in view of at least one of these complexes. Each complex has a 70-m antenna and a number of 34-m antennas that provide the radio communications and radiometric measurements (observables including Doppler, range, and interferometric types for navigation and science) with NASA's spacecraft. The DSN's central control and test facilities are located at the Jet Propulsion Laboratory (JPL) in California. It may be useful to note that the DSN is not limited to Earth stations. Being a communications network, one end of the communications link is on the ground and the other end is in space onboard spacecraft or on a planetary landed asset.

A number of innovative hardware, software, and procedural tools are used at the DSN complexes and the network control at JPL for day-to-day operations of the deep space network. Systems and technologies employed by the network include large aperture antennas (34-m and 70-m), cryogenically cooled receivers, high-power transmitters, stable frequency and timing distribution assemblies, modulation and coding schemes, spacecraft transponders, radiometric tracking techniques, etc. The DSN operates at multiple frequencies, including the 2-GHz band, the 7/8-GHz band, and the 32/34-GHz band.

To meet the ever-increasing resource demands of NASA missions and its international clients, the DSN continues to evolve via investments in relevant technologies and advanced systems. These investments in communications and tracking studies and developments are managed at JPL through the Advanced Systems Program, which enables DSN evolution and long-term innovation. This paper introduces Advanced Systems Program tasks[1], discusses recent accomplishments, and addresses product infusion. Current program focus is on increasing the downlink and uplink bit rate capabilities by factors of 10 and 1000, respectively, improving radiometric accuracy by at least a factor of 2, and reducing operational complexity and cost. These goals are achieved via investments in a new software-radio transponder; a new low-mass, high-stability space clock; new coding techniques; novel approaches in radiometric measurements and media calibration; and more.

The advanced systems investment guidelines include the DSN Level 1 requirements, flight missions' needs, a long-term view of DSN communications and tracking, sponsor directions, and DSN systems engineering and strategic planning inputs. The measures to assess investment effectiveness are link throughput, tracking accuracy, system robustness, operational cost savings, and infusion potential.

2. Advanced Systems Program Investments

Figure 1 shows recent Advanced Systems Program investment tasks, which are loosely grouped as uplink, end-to-end, tracking and pointing, and radio-frequency (RF)/optical. The activities are synergistic and together provide for DSN enhancements. Hence, some of the products must be developed concurrently in order to ensure useful functionality.

2.1. Uplink

The purpose of the uplink tasks is to provide backup and/or an alternative to the 70-m asset. There are two main efforts that address the above goal [1]. In the first, the power level of the 34-m antennas is increased to yield effective isotropically radiated power (EIRP) levels equal to the 70-m EIRP. In the second approach, antennas are arrayed to deliver EIRP levels equal to or exceeding the 70-m antenna capability.

Presently, both the 70-m and 34-m assets use 20-kW X-band klystron power amplifiers; hence, the 70-m assets generate about four times more EIRP than the 34-m ones. By increasing the 34-m power capability to 80 kW, the 34-m assets can generate about the same EIRP as the 70-m assets. The effort to increase the 34-m power level to 80 kW completed in early 2009, and this development is now being infused in the DSN. Specifically, it will be implemented in a new 34-m antenna for the Australian complex.

Two concepts were developed and implemented to increase the 34-m antenna X-band power: 1) Extended the existing tri-band (Xup/Xdn/$K_a$dn) feed from 20 kW to 80 kW through modification of the uplink injection section, and 2) designed, constructed, and tested a prototype ladder combiner to generate 80 kW from the aggregation of 20-kW amplifiers. To handle the added power density, the feed and the feed junction were redesigned with two slots rather than a single slot, resulting in reduced power density at the high power signal's point of entry into the feed [2]. Figure 2 shows the abstract presentation of the feed with feed arms. Figure 3 shows the feed with uplink and downlink subsystems.

The other technique for improving uplink capability is antenna arraying [3]. Two approaches (Figure 4) have been pursued to demonstrate uplink arraying feasibility. In one, Goldstone 34-m antennas were arrayed [4]; in the other approach, five 1.2-m antennas were arrayed [5]. Table 1 gives examples of uplink arraying options, with the resulting EIRP for each option. Uplink arraying clearly offers the promise of delivering EIRP levels much higher than the existing capability.

The key challenge in uplink arraying is the phase alignment of the array elements. Both Advanced Systems Program experimental campaigns have shown that the phases can be calibrated to last for long periods of time (more than a week). Figure 5 shows the bit error rate measurement made by the experiment using five 1.2-m antennas. The loss compared to a single antenna uplink is very small. It is envisioned that an operational uplink array will function with less than 1 dB of arraying loss (probably about 0.5 dB of loss).

Presently, the effort is focused on the demonstration of uplink arraying for non-communications applications. These applications include radiometric measurements, radio science, and solar system radar [6].

Antenna Diameter, m	Power, kW	Array Size	EIRP, GW	Notes
70	20	1	360	Existing
34	20	1	85	Existing
34	20	3	765	Possible future
12	2	31	1000	Possible future
3.8	430	217	1000	Possible future

Table 1. Examples of Uplink Arraying Options for Signal Transmission to Interplanetary Spacecraft at 7.2 GHz

2.2. End-to-End

The end-to-end set of tasks includes a high-performance space transponder, high-performance ground receiver, state-of-the-art channel coding, and precision frequency and timing distribution at DSN complexes.

2.2.1. Transponder

The majority of deep space missions currently use small deep space transponders (SDST) This transponder has been in use for about ten years and is plagued by limited performance and possibly parts obsolescence. Therefore, the Advanced Systems Program is developing a new product, the universal space transponder (UST) for use by post-2015 missions. In addition to SDST parts obsolescence concerns, missions are likely to select UST instead of SDST because of the following UST features:

- An order of magnitude downlink rate increase (150 Mb/s)
- Three orders of magnitude uplink rate increase (25 Mb/s)
- Software radio flexibility and compliance with NASA Space Telecommunications Radio System architecture
- Frequency agility providing for channel selection after launch
- Uplink channel decoding
- New as well as legacy downlink channel coding that includes integrated turbo and low-density parity-check (LDPC) telemetry encoding
- Improved radiometric observations with regenerative pseudo-noise ranging

- Multi-frequency and multi-function radio with direct-to-Earth and proximity capability (UHF/S/X/Ka)
- Cost savings from flying one less radio
- Reduction in DSN antenna usage
- Increased uplink reliability
- Operational flexibility

2.2.2. Advanced Receiver

To accommodate the increased downlink capability of the DSN, the Advanced Systems Program is developing the advanced receiver [7] to be compatible with UST. The salient features of the advanced receiver are the following:

- 500-MHz bandwidth compared with current 72 MHz capability
- Continuous data rate from 8 bps (BPSK) – 640 Mbps (QPSK, higher for advanced modulations)
- Demodulation of bandwidth-efficient modulations, including square-root raised-cosine (SRRC) and Gaussian minimum shift keying (GMSK)
- LDPC and legacy convolutional, RS and concatenated
- Decoded bit rates 2 b/s to 320 Mb/s [quadrature phase shift keying (QPSK) with rate ½ code]
- Acquisition with symbol energy/noise power spectral density (Es/No) as low as −8 dB
- Doppler observables with precision time tagging
- Delta-differential one-way range (Δ-DOR) support
- Uses wideband VLBI science receiver (WVSR) hardware
- Predict-driven numerically controlled oscillator (NCO) for Doppler compensation
- Phase-continuous tuning
- Frequency resolution of 5 mHz with 1 Hz update
- Engineered for reconfigurability
- Waveform recording bandwidth up to 32 MHz internal, up to 160 MHz external

The system architecture differentiates between wideband and narrowband waveform processing by allocating higher speed processing to field-programmable gate array (FPGA)-based hardware. Narrowband processing is performed in software that operates on sampled data that have been down converted by the reconfigurable hardware. Limited-duration waveform data storage provides reprocessing opportunities, if needed. Figure 6 shows the receiver architecture. A future update will incorporate a range measurement feature.

In summary, the receiver is a fully digital system and will be capable of meeting the requirements of NASA's communications and tracking services. The intelligent property (IP) can be adapted to hardware platforms provided by industry. The IP fits into the architecture envisioned by NASA's Space Communications and Navigation office for Tracking and Data Relay Satellite System (TDRSS) ground station upgrade.

2.2.3. Coding

The recent focus of Advanced Systems Program coding studies has been the development of uplink codes [8, 9]. Traditionally, DSN only uses uplink coding for error detection but not for error correction. Due to the low bit rate uplink capability of the SDST (2.4 kb/s), the uplink normally operates with adequate margin, hence alleviating the need for uplink coding. However, with the development of the new transponder (UST), the uplink rates will drastically increase, resulting in a shortage of uplink margin. To remedy this, Advanced Systems Program has developed uplink codes that will be infused in UST. The codes have been optimized for four types of applications and can provide coding gains of about 5 dB to about 9 dB. Table 2 provides useful information on the uplink codes.

Table 2. Summary of Uplink Codes for UST Infusion

Purpose	Block Length, kbits	Throughput, kb/s	Approximate Coding (Gain), dB
Emergency	0.1	0.01	5
Command/ARQ	0.1– 1	1– 4	7
File upload	1– 4	1,000	8
Human Support	> 4	20,000	9

2.2.4. Stabilized Photonic Links

Motivations and applications of stabilized photonic link technology for signal transportation are metrology, operational performance verification, and antenna arraying. Fixed-frequency reference distribution is required for metrology (e.g., 100 MHz, 1 GHz). Test signals need to be transported for calibration purposes. And very stable signal distribution is needed for antenna arraying [10]. The present fiber optic distribution assemblies at DSN complexes are aging, and are, therefore in need of replacement and upgrade.

The technical approach consists of the following two activities:

- Develop, demonstrate, and study trade-space for stabilized, narrowband (single-frequency) approach using electronic compensation

- Develop, demonstrate, and study trade-space for stabilized, broadband (any frequency of interest) approach with compensation through physical control of fiber length variations

Both of these approaches were developed during 2008 and 2009, with testing and validation to be completed in 2010. Figure 7 illustrates the frequency stability of the broadband system as measured in the laboratory. The Allen standard deviation is 10^{-16}. The developed techniques will be ready for infusion in late 2010 or early 2011.

2.3. Tracking and Pointing

The tracking and pointing category consists of four tasks: radiometric studies deal with improvements in VLBI, Doppler, and range measurements; low cost-water vapor radiometer system will provide better calibration of the troposphere; monopulse calibration using a radio source will improve pointing performance of Ka-band ground antennas; and space clock will provide an accurate frequency source onboard spacecraft.

2.3.1. Radiometric Studies

The following are some of the radiometric activities and products:

- Error budgets: Develop and maintain error budgets for radiometric tracking applications, including Δ–DOR, range, and Doppler. Long poles in the error budget are identified and appropriately addressed to reduce error in radiometric tracking.
- High-frequency radio reference frame: Develop a radio reference frame at Ka-band [11]. This is accomplished via the use of DSN antennas as well as other ones such as the very long baseline array (VLBA) assets. Figure 8 shows the current state of the radio reference frame.
- Validation of radiometric tracking using uplink arrays: The objective is to show that uplink arraying is capable of delivering Doppler and range products with the same quality as a single-antenna system [6].
- Optimum radiometric uses of advanced water vapor radiometers (AWVRs) in the DSN.
- Δ -DOR improvements to 1 nanoradian accuracy via hardware and procedure improvements, including faster distribution of Earth orientation parameters (EOP), wide-band reception, AWVR calibrations, etc.
- Demonstration of spacecraft phase tracking capability using VLBA and Australia Telescope National Facility antennas
- Spacecraft-to-spacecraft and same-beam interferometry, with emphasis on Mars approach tracking. The objective is to increase Mars approach orbit determination accuracy. It has been shown that this approach can reduce Δ-DOR residual to about 3 picoseconds [12].

2.3.2. Space Clock

Under this task, a low-mass atomic clock with long-term stability of 10^{-15} is being developed for flight. Many benefits are envisioned from flying a stable source that includes both science and operational advantages [13]. An important operational benefit is to provide for one-way navigation (downlink only). The stability of the clock alleviates the need for an uplink to conduct navigation functions [14].

NASA missions will receive the following benefits from an ultra-stable clock:

- Less need for specialized uplink DSN passes for spacecraft navigation
- Only downlink is required for navigation
- Single DSN antenna tracks multiple orbiters at Mars — 4 to 8 $M/yr/spacecraft savings over 2-way tracking
- Navigation duties can be shared with other radio antenna sites (operating in listen-only mode)

In addition to the above, radio science endeavors may also benefit from the space clock. Space clock provides long-term stability to an ultrastable oscillator (USO), as depicted in Figure 9. The prototype physics package under development is shown in Figure 10, and Figure 11 shows the clock performance with a long-term stability of 10^{-15} or better.

2.4. Hybrid Ground Station

For future operations, the DSN plans to use deep space optical communication, which can provide a high-capacity downlink. It is envisioned that, in addition to this new capability, RF communications will continue to be used for standard capacity downlink and uplink. Thus, the future DSN will include RF and optical communication links.

The design of the RF ground station is mature, while the optical ground station design is presently the subject of research and development. Several studies have been carried out on the design of the optical communication ground station, with concepts ranging from a single 10-m class station to arrays of small independent telescopes.

Since both links will exist in the future DSN, it is natural to ask whether the two types of ground stations might be combined to result in cost benefits. In addition, significant operational benefit can result from a simple co-location of the RF and optical facilities at the existing DSN sites.

Efforts to develop a hybrid station must address the following challenges, among others:

- Use of the same reflector surface for both RF and optical signals without increasing RF receiver noise temperature and without severe optical losses
- Durability of optical surfaces, with their stringent roughness requirements, without a radome to protect them from atmospheric elements
- Separation of optical and RF signals
- Guiding the separated signals into their respective detectors

In addition, the following issues need attention to successfully develop a hybrid ground station:

- The RF and optical beam directions are slightly offset with respect to each other due to the differences in the air refraction coefficient at the respective wavelengths. Thus, optical steering mirror design and RF pointing must consider this effect.
- The current DSN sites were selected for their suitability for RF communications. Careful observation and analysis of the optical channel at DSN sites are required to determine the suitability of the site for optical communications.
- Last, but not the least, is the problem of keeping a large structure stable for optical wavelengths. Large antennas can experience deformation due to gravity, wind, and other elements.

Presently, the Advanced Systems Program is making design tradeoffs to select a baseline approach, and channel data are being collected at Goldstone to characterize the site. Figure 12 shows a shared aperture design concept under development. In this approach the central area of the large RF antenna (i,e., 34 m) is shared between RF and optical signals.

3) Summary

The DSN communications and tracking Advanced Systems Program invests in research and development efforts that will enable the DSN to meet its customers' needs in the future. The tasks supported by this program collectively focus on the realization of the goals and objectives of DSN road map and its Level 1 requirements.

The current focus of the program can be summarized as follows:

- Order(s) of magnitude improvements in uplink and downlink performance
- A factor of 2 improvement in Δ-DOR tracking accuracy
- Increased operational flexibility and cost savings for DSN and flight missions
- Preparations for potential 70-m antenna retirement

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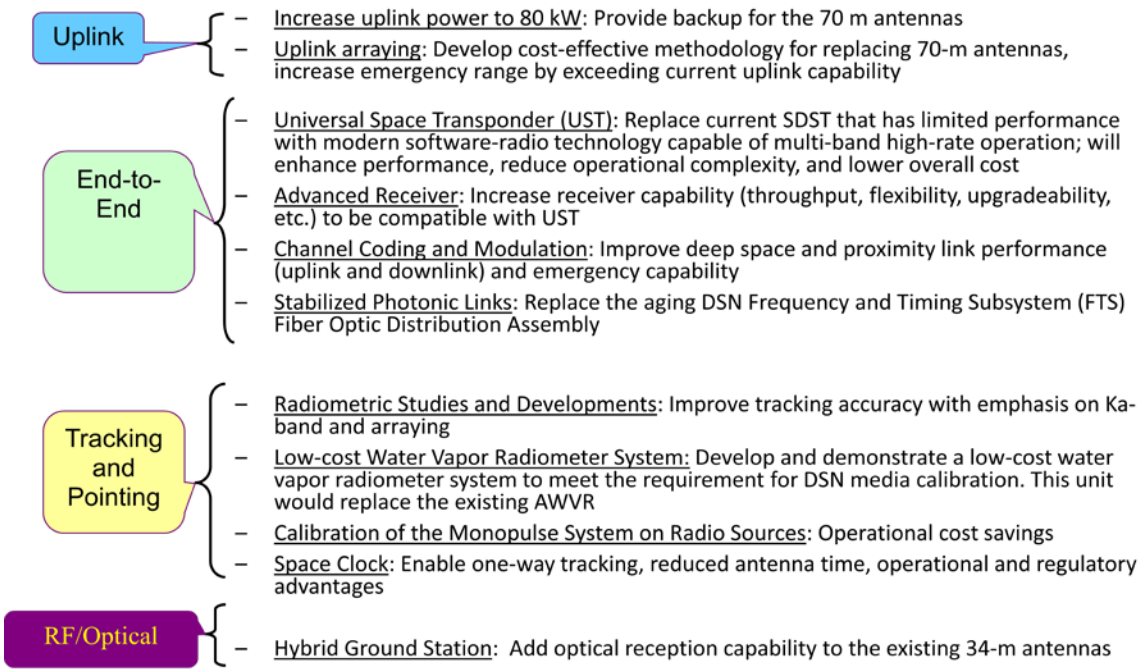

Figure 1. Recent Investments of the Advanced Systems Program

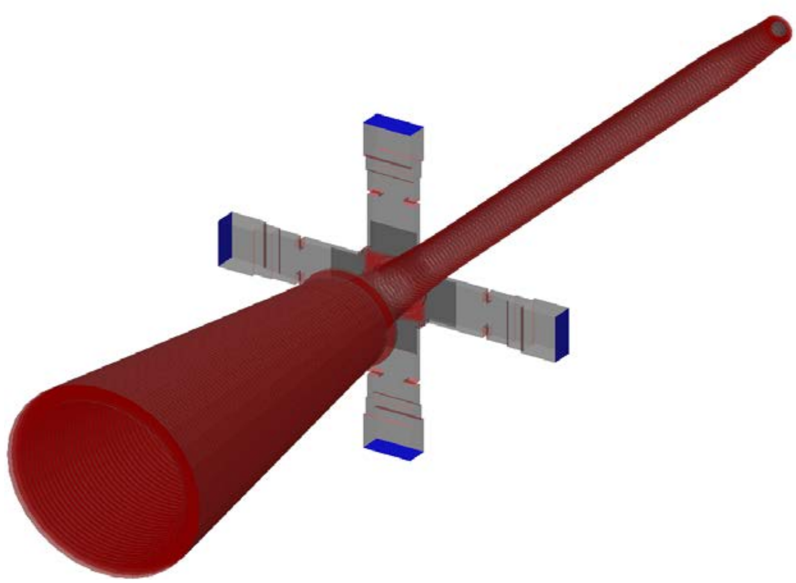

Figure 2. The Abstract Presentation of the Feed and the Arms

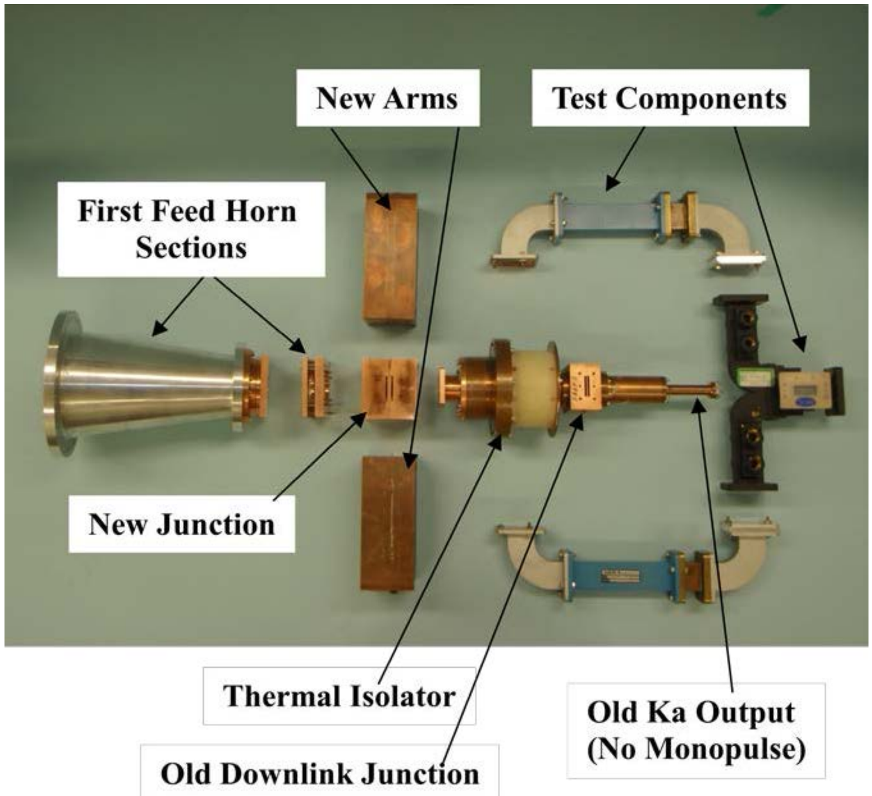

Figure 3. The Feed System with the New Two-Slot Junction

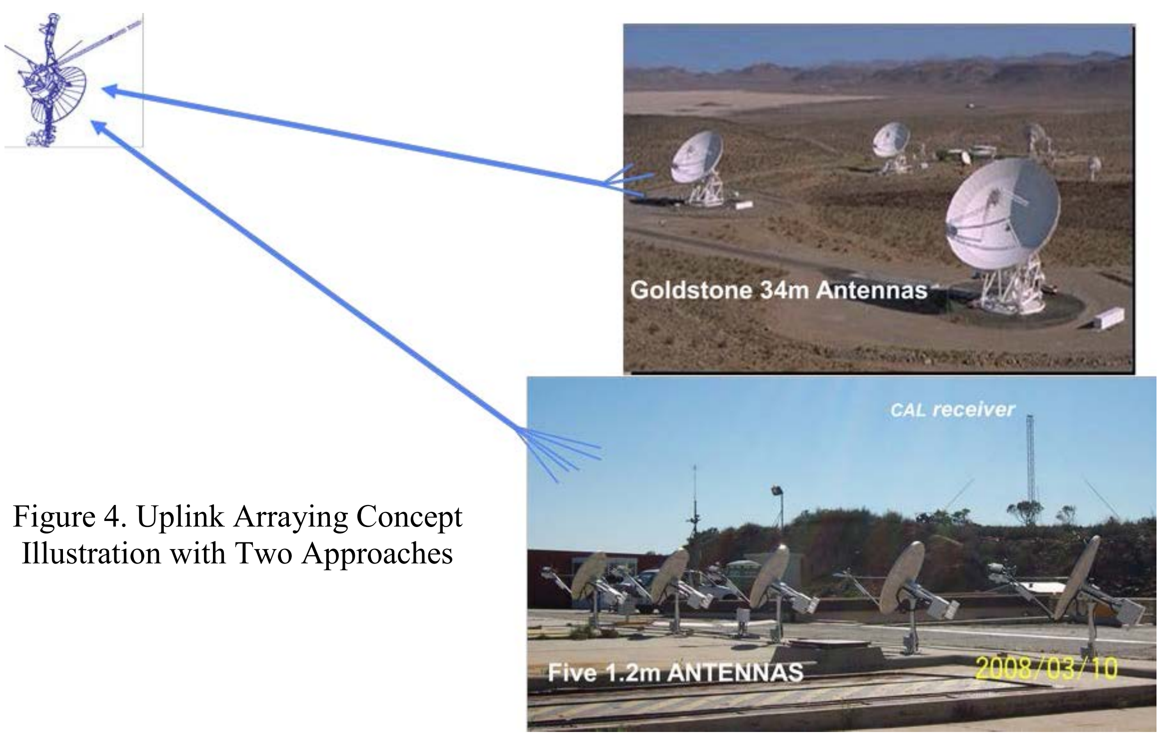

Figure 4. Uplink Arraying Concept Illustration with Two Approaches

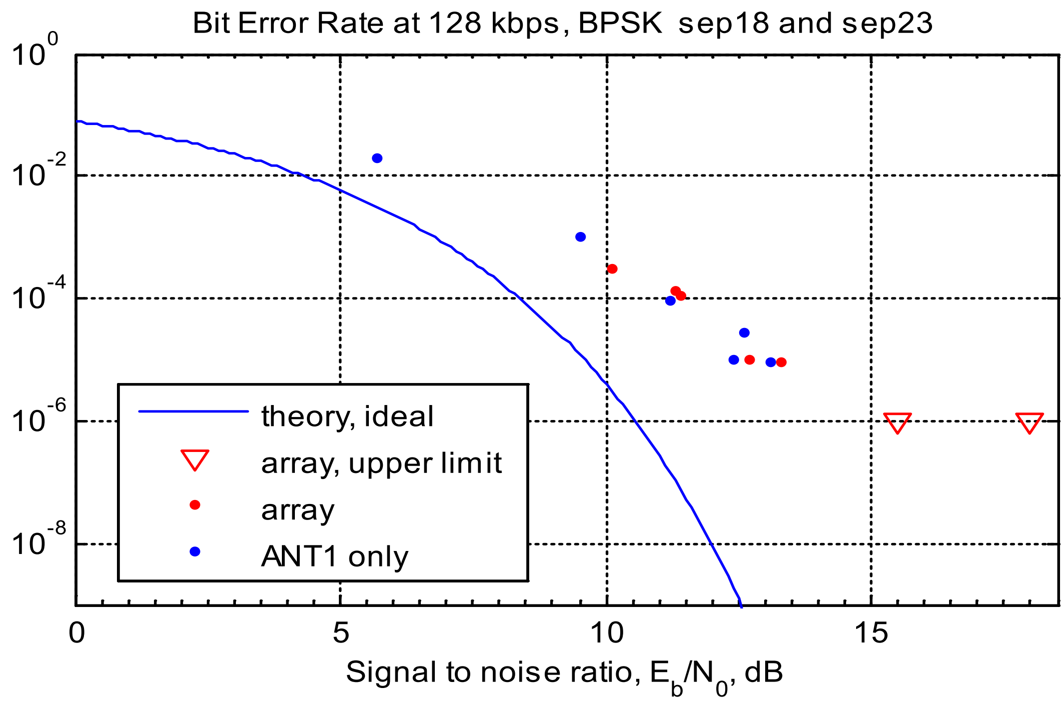

Figure 5. Measured Bit Error Rate in an Uplink Arraying Experiment

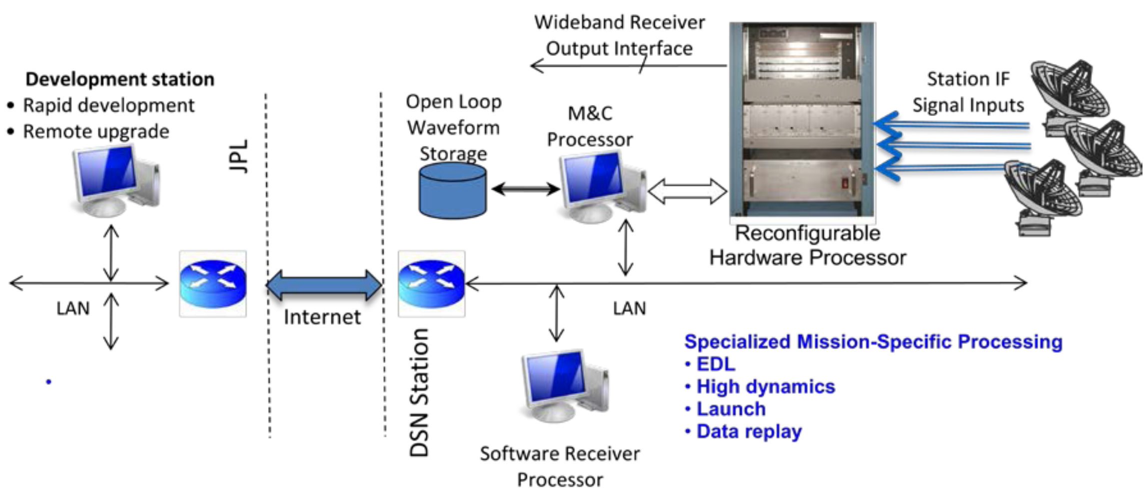

Figure 6. Receiver System Architecture

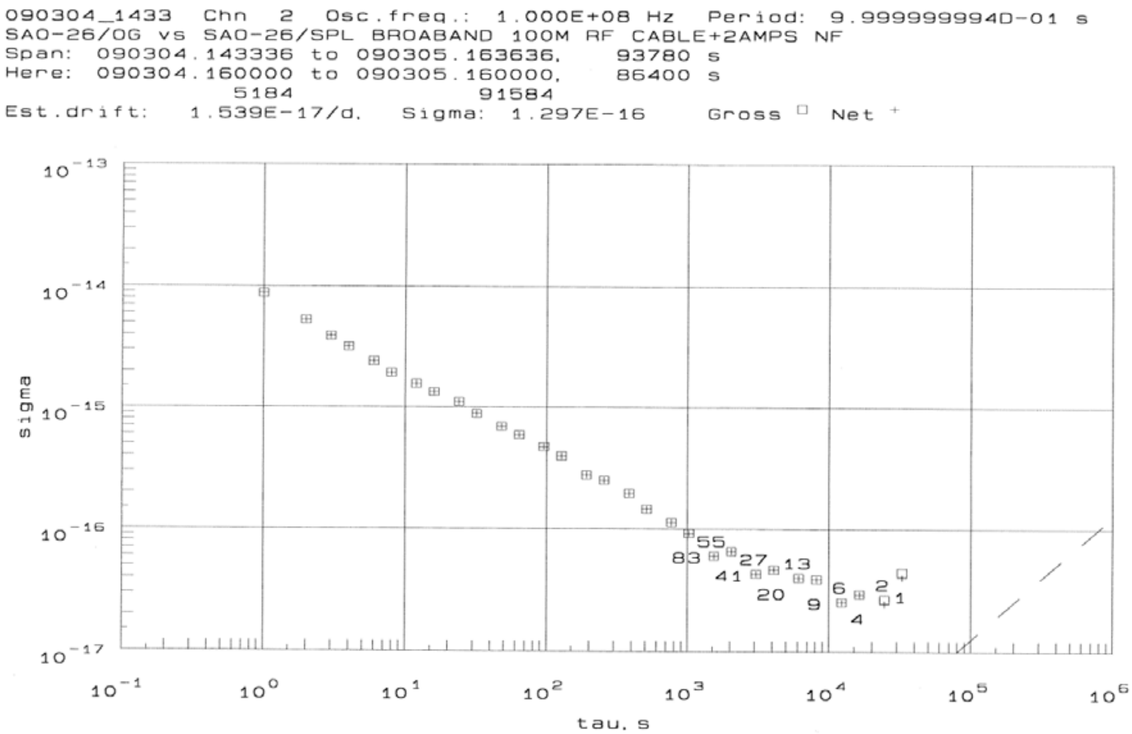

Figure 7. Measured Signal Stability with the Broadband System

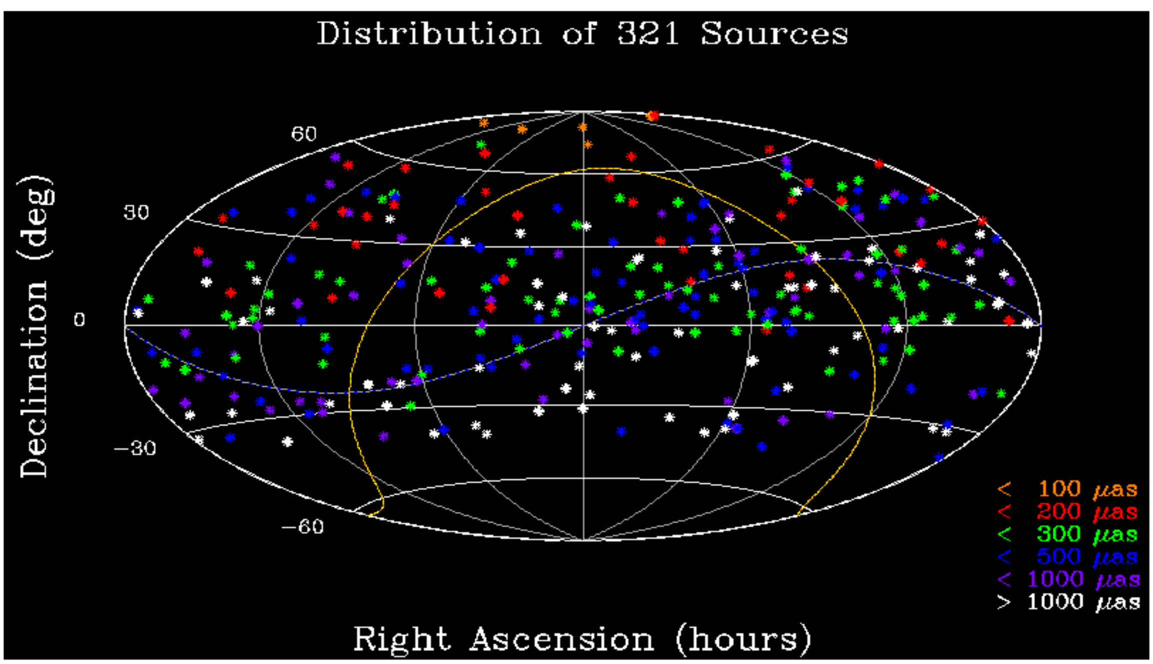

Figure 8. The Present Status of the High-Frequency Radio Reference Frame

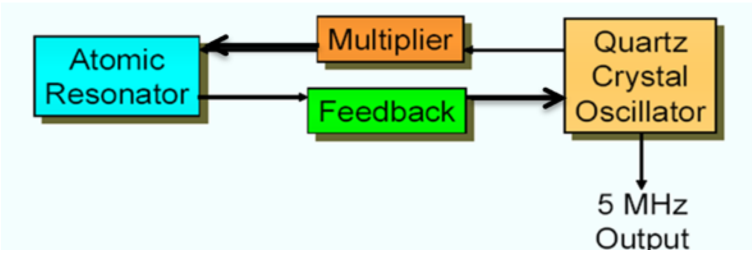

Figure 9. Stabilization of a Crystal Oscillator by an Atomic Clock

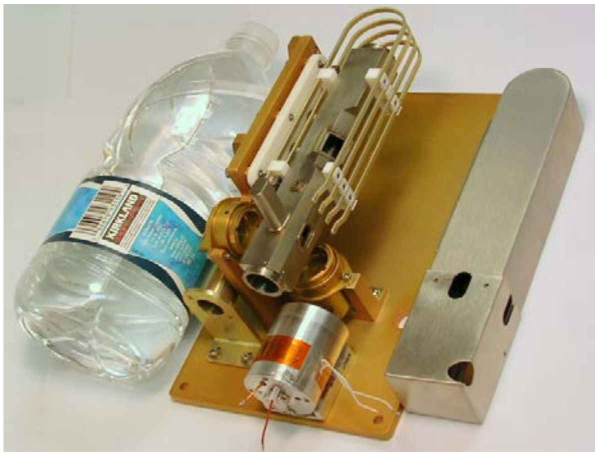

Figure 10. Space Clock Physical Package (with a 1-liter bottle for size comparison)

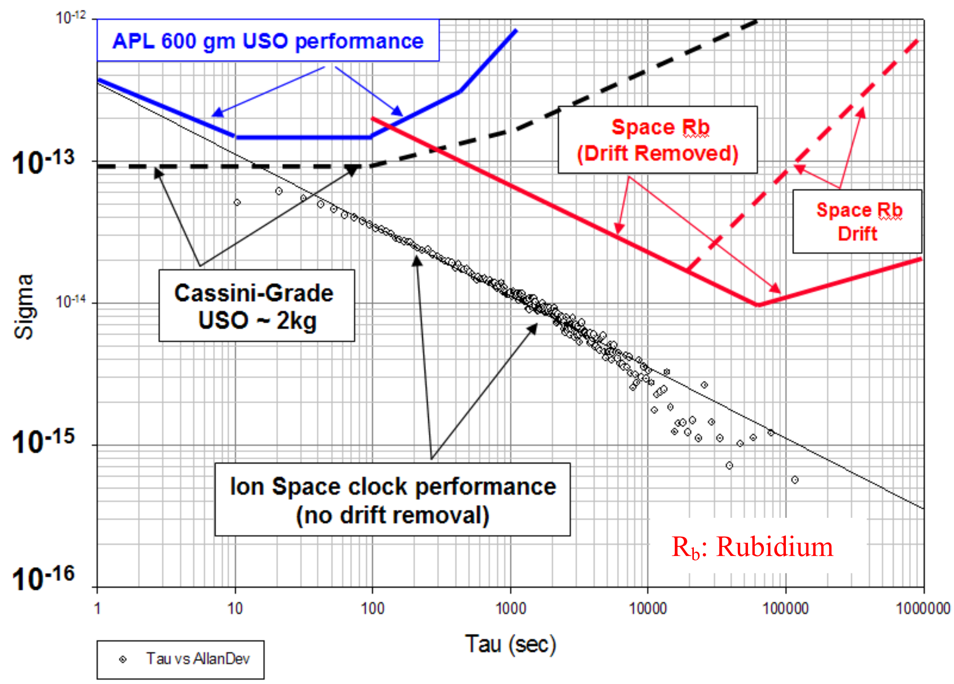

Figure 11. Space Clock Performance

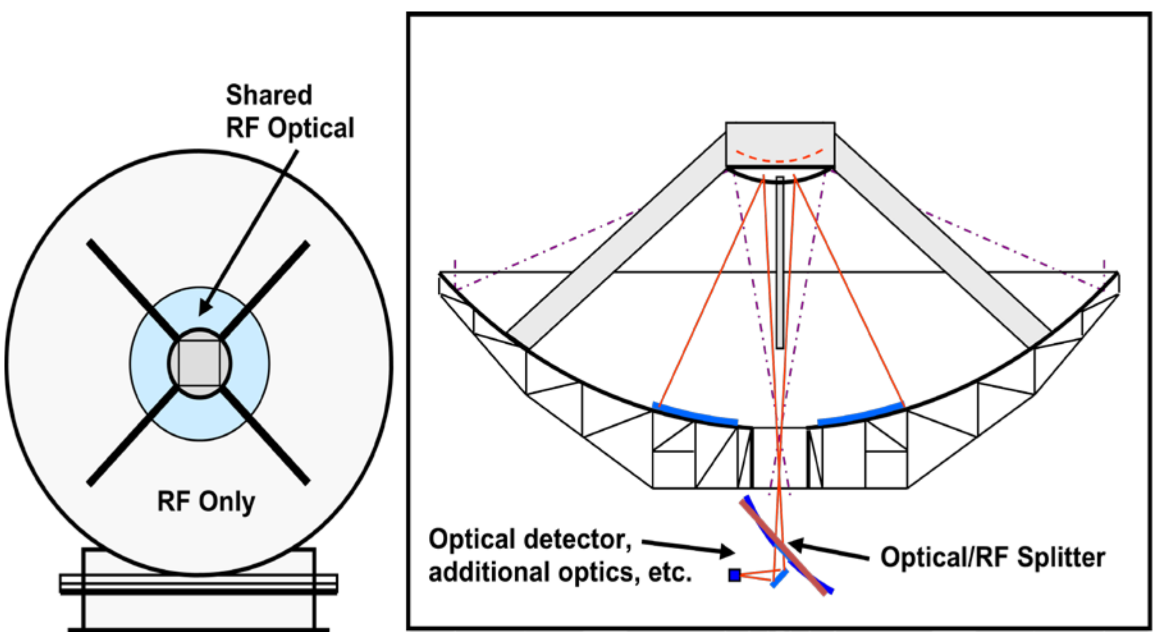

Figure 12. The Shared Aperture Design