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How the World Uses the Deep Space Network's Technology

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ABSTRACT. — The Deep Space Network (DSN) and its predecessors have contributed to the development of a great deal of technology. Much of this has been used by others, in building ground stations, in building spacecraft, and in many other ways. This article tells about some of that technology and its subsequent use.

I. Introduction

On December 24, 1963, W. H. Pickering, the director of the Jet Propulsion Laboratory (JPL), issued a memo establishing the Deep Space Network (DSN), combining three previous organizations: the Deep Space Instrumentation Facility, Interstation Communications, and the mission-independent portion of the Space Flight Operations Facility. On February 20, 2014, the DSN celebrated its 50th anniversary with a symposium. This article is the written version of the talk "How DSN Technology Changed the World," given by the author at that symposium.

The DSN and its predecessors have brought enormous capabilities to deep space communication through an active technology program and excellent engineering. These advances have been obtained by all possible means — developing new technology, building on other people's technology, and using completed ideas.

We know that the DSN, built on this technology, has brought planetary science and all the rich results from that. We have no idea how much it affected the cold war. It has also brought remarkable pictures of the solar system that have become almost unremarkable because we see them so often.

In many cases, it's hard to tell how other entities have used technology that we've developed. We publish what we've done and we are not necessarily aware of how it's used. Just as DSN technology is often based on ideas previously used elsewhere (often radio astronomy), other people's developments are based on ours. We don't know how much has been based on DSN technology but not published because of security, or proprietary interests, or lack of time and energy.

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The DSN's predecessors began work at the dawn of digital communications. Over the years, digital technology has taken over our world. Because of its need for very low-signal communications, the DSN began using and developing digital technology very early.

Radar holds a special place in this. Besides its own planetary exploration, the DSN's planetary radar has aided in the development of technology, has allowed testing of technology, has aided in the development of spacecraft missions, and has saved spacecraft missions. The DSN has been used successfully for scientific radar since 1961 [1]. It has allowed new DSN technology to be tested without using (often non-existent) spacecraft. As a scientific instrument, the Goldstone Solar System Radar has been used to image asteroids, the Moon, Mars, and other objects in the solar system [2]. Its first use at Venus changed our knowledge of the astronomical unit by nearly two orders of magnitude [3]. It has been used to determine landing sites on the Moon and Mars. It is used to learn about asteroids and space debris. It saved the European Space Agency/National Aeronautics and Space Administration (ESA/NASA) Solar and Heliospheric Observatory (SOHO) mission by locating the spacecraft, which had lost lock on the Sun, when normal operations had not made contact for days [2].

We divide technology developed by and for the DSN according to groups who used it later:

- It has been used for radio astronomy and at other space agencies' ground stations.
- It is used in spacecraft.
- It is used in the rest of the world.

II. Contributions to Radio Astronomy and Ground Stations

Looking first at the use of DSN technology for radio astronomy and by other space agencies' ground stations, consider very long baseline interferometry (VLBI), which was originally developed for radio telescopes. Based on that, the DSN developed a VLBI capability in order to collaborate with researchers around the world using VLBI for astronomy, astrometry, and geodesy [4]. The DSN developed an adaptation for spacecraft angular position measurements — this was delta differential one-way ranging (delta-DOR), first used by the DSN [5]. Delta-DOR is now used widely by other space agencies [6,7].

Low-noise amplifiers were needed by the DSN, and those developments are used elsewhere. A compact, cryogenically cooled, choked waveguide for low-noise input coupling into a cryogenically cooled amplifier has been used by radio astronomers as well as by ESA, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the German Research and Development Institute for Air and Space Travel.[1] The National Radio Astronomy Observatory (NRAO), the Max Planck Institute, Caltech's Owens Valley Radio Observatory, and Princeton University have all used the reflected-wave maser developed in the early 1970s [8]. Cryogenically cooled traveling-wave masers and closed-cycle refrigerator systems, developed both in the early 1960s and late 1970s, were later used at Arecibo Observatory.[2]

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[1] Robert Clauss, personal communication, April 16, 2014.

[2] Robert Clauss, ibid.

When considering high-level design for new 34-m antennas, the DSN adopted the concept of a beam-waveguide feed from the larger Japanese Institute of Space and Astronautical Science (ISAS) (now Japan Aerospace Exploration Agency, or JAXA) 64-m antenna, and developed a wideband, high-efficiency, low-noise beam-waveguide system wherein electronic equipment is below ground for ease of access and station electronic stability [9]. ESA and the Indian Space Research Organization (ISRO) have constructed similar 30-m-class beam-waveguide ground antennas for data reception from deep space.[3]

Radio science, the use of received radio signals to learn about a body's atmosphere, has been done by the DSN since the 1960s. ESA has used techniques developed by the DSN, starting with Mars Express, in the past few years.[4]

III. Contributions to Spacecraft Technology

Looking at DSN technology contributions to spacecraft, early DSN technology work demonstrating a quasi-optical ferrite circulator as part of a system to phase lock an existing high-power 34.5-GHz (Ka-band) oscillator led to a successful implementation of a similar circulator on the CloudSat spacecraft.[5]

The DSN supported the "lossless" Rice compression algorithm, although it was developed by the Voyager mission [10]. The DSN technology program carried out "lossy" data compression work before it was accepted by spacecraft teams [11]. The Galileo S-band mission gave imaging teams a reason to take lossy data compression seriously [12]. The "ICER" system, developed in the DSN technology program, has been used for onboard compression of thousands of images by the Mars Exploration Rover and the Mars Science Laboratory missions, and for the Solar Terrestrial Relations Observatory spacecraft [13].[6]

The development of the mercury ion standard (microwave transition in mercury ion), an atomic clock for navigation, is being supported by NASA for spacecraft applications [14].

IV. Contributions Outside Space Exploration

The space program is not the only part of society that has gained a lot from DSN technology developments. Pseudonoise (PN) codes were used first for jam-resistant radio guidance systems for missiles [15]. Later PN codes were developed for other applications, including planetary radar and ranging measurements [16]. Today, PN codes are used in many communications and navigation applications, including the Global Positioning System (GPS), code-division multiple-access cellular telephony, radar, and military communications [17,18,19,20].

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[3] Dan Bathker, personal communication, April 2, 2014.

[4] Sami Asmar, personal communication, May 12, 2014.

[5] Dan Hoppe, personal communication, April 1, 2014.

[6] Aaron Kiely, personal communication, March 24, 2014.

Though the phase-locked loop (PLL) was developed before the advent of digital communications, it was the subject of a great deal of research at JPL during the 1950s and early 1960s. It was customized for new applications, including detecting and tracking a narrowband signal in wide-band noise, and the theory was developed [21]. Today, besides being used in space communications, the PLL is used for frequency synthesis, carrier synchronization, PN code synchronization, and bit synchronization [22,23]. A typical smart phone has several PLLs [24].

Frequency standards have been used in many places. The cryogenic oscillator, developed at JPL in support of radio science, is used worldwide in several national meteorological labs [25]. The opto-electronic oscillator has been commercialized and is being pursued in many places; the opto-electronic oscillator based on JPL's whispering-gallery mode resonator has been adopted by the Department of Defense and has flown in missiles [26].

The fiber optic frequency distribution system developed for the DSN is now used widely for time and frequency distribution and dissemination. It was used as the first fiber optic system in space aboard the Shuttle Radar Topography Mission [27]. It's the basis for the widely used fiber optic based cable television. It is used for distribution of optical frequency standards in Europe and Asia, and is being developed for the same use in the United States.[7]

With the need for communication at extremely low signal-to-noise ratio, the DSN made huge strides developing error-correcting codes. Many of these codes were mathematical curiosities before they were developed and particular examples were found by the DSN, making them practical. Even though, contrary to popular myth, no class of error-correcting codes appears to have been "invented" at JPL, the results of the DSN's technology development have been huge. Neither Reed-Solomon codes nor Viterbi decoding, nor even the idea of concatenating codes, was invented at JPL, but the concatenation of Reed-Solomon codes with Viterbi-decoded convolutional codes began with Voyager 2 [5]. That construction became popular for a lot of purposes, was standardized by the Consultative Committee for Space Data Standards (CCSDS), and was adopted as the first generation DVB-S digital television broadcast standard [28]. Convolutional codes are ubiquitous in communications [29], as are Reed-Solomon codes in data storage [30]. The work done for NASA and the DSN in the 1960s, determining the best short-constraint-length convolutional codes, led to the constraint length 7, rate 1/2 code that is now one of the most widely deployed channel codes [31].

Similarly, specific turbo codes and low-density parity-check (LDPC) codes developed in the DSN technology program are now available as commercial products from several companies. The 3G and 4G cellular standards use codes of these types (though they are not the same codes, precisely) [32]. JPL is responsible for inventing and developing the concept of "protograph LDPC codes," in which a small protograph serves as a basis for building a larger graph that defines the code. This was a breakthrough in the field, because it enabled low-complexity encoders and decoders to be built for the highest performing LDPC codes [33].

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[7] Lute Maleki, personal communication, April 1, 2014.

VI. Parting Thoughts

Communications and data storage are not the only areas to gain from DSN technology developments. Computer tomography can be traced to VLBI [34]. And not just high-tech electronics have benefitted from DSN technology development. The pedestal for the 70-m antenna at Goldstone, DSS-14, was made from the best quality crushed rock. Unfortunately, there was chemical degradation (called reactive aggregates) in the rock, and so the DSN called in people who built freeway bridges and overpasses. The DSN experience with the weakening effect of reactive aggregates on massive, precision concrete structures contributed significantly to the general body of knowledge on this subject that existed at the time. Eventually, the problem became of concern to the public agencies responsible for the design of concrete structures involved in highway construction.[8]

DSN technology development is not as big as it once was, but developments are still affecting the outside world. The superconducting nanowire single-photon detector recently developed for the DSN is being explored in laboratories around the world in quantum optics experiments and spectroscopy experiments. Potential applications also include quantum cryptography and remote sensing [35].

It will be interesting to see what is to come. Technologies developed for deep space optical communications, the Mars Network, and delay (or disruption) tolerant networking may well find their way into other space exploration or the rest of the world.

During most of the last 50 years, NASA Headquarters supported DSN technology programs, usually called the Advanced Systems Program. Many of these developments came from that program. It allowed these developments, and gave stable funding to people making the developments. It also meant that engineers had analyzed a great number of possibilities, and were therefore able to react to emergencies of many sorts. Many of its developments are summarized in [36].

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[8] Doug Mudgway, personal communication, quoting his conversation with Don McClure, March 27, 2014.

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