Retelling the Story:
"Architecting the Deep Space Network (DSN): Why We Set It up the Way We Did"
by Eberhardt Rechtin
Thursday, August 25, 2000
Retold by Claire Marie-Peterson with Teresa Bailey and Eberhardt Rechtin

This was not my first experience with JPL Stories, so I knew to arrive at the library early for the 4 p.m. start of the fifth installment in the series: "Architecting the Deep Space Network (DSN): Why We Set It up the Way We Did," presented by Eberhardt Recthin, identified on the announcement flyer as "the 'father' of the Deep Space Network." When I arrived with my cup of spearmint tea at 3:50, the room was already half full and buzzing with conversation. This was the place to be that Thursday afternoon for what turned out to be 100 to 120 JPLers grey, green, and everything in between. "Is that Tom Vrebolovich?" someone asked, as a lanky grey-haired fellow with an enormous agate tie clasp took a seat near the front. "He must have retired twenty years ago."

On a display board behind the storyteller's chair a series of vintage black-and-white photographs portrayed an earnest young man in tweed and bow tie—drawing on a blackboard, conferring with colleagues, and otherwise looking every inch the aspiring engineer of the post-World War II era. Just to the right, leaning against the circulation desk, was a monumental, framed watercolor of a scene recognizable to the untrained eye as the Goldstone, California station of the DSN. Soon enough, the storyteller himself stood at the front of the room—a bespectacled, tan gentleman with fine, wavy, white hair, his mouth still turned down earnestly at the corners. He was dressed, it occurred to me afterwards, like a live oak—his shirt the familiar dark, brownish green that dominates many a Pasadena vista, his slacks a tree-trunk tan.

Teresa Bailey, head of the storytelling team at the library, introduced the speaker. The watercolor, we heard, was a gift to JPL from Dr. Rechtin, who had received it from the Caltech Management Association with their Excellence in Management Award—one of many professional honors conferred upon him in the course of his illustrious career—or rather, careers.

Most recently, he was Professor of Engineering at the University of Southern California, where he established a graduate program in system architecture that gave him occasion to teach many current JPLers who had been enrolled in the program over the years—a group well-represented in present company, I sensed, from grunts of recognition throughout the talk. Before that, Dr. Rechtin was CEO of Aerospace Corporation from 1977 to 1987, Chief Engineer at Hewlett-Packard from 1973 to 1977, and a high-ranking member of the Department of Defense from 1967 to 1973. But his story today would center on his first career, the one that began at JPL in 1948, while he was still working on his Ph.D. at Caltech, and extended to 1967, by which time he had become an Assistant Lab Director. In the years in between, Teresa told us, "he had invented much of the early technology for deep space communications and developed the Deep Space Network architecture. This is why we know him today as the father of the DSN. In an oral history interview, Dr. Rechtin acknowledged his most influential Caltech professor and mentor—and later his boss—was Dr. William Pickering, JPL Laboratory Director from 1954-1976. He is," Teresa said, "certainly one of the major branches—if not roots—of our JPL family tree."

When Dr. Rechtin took the floor, he played down the remarkable breadth of his professional experience. His many careers, he said, showed that there was indeed life after JPL—though it wasn't nearly as good. He delivered such lines with perfect deadpan seriousness—his earnest mouth erupting into brilliant white with the audience's response. He was at ease in the role of storyteller, immediately contradicting what we may have read in books about the Deep Space Network. It began in 1952, he calmly stated, not 1958, as the history books would have it. And as the chief (though not the only) architect of the DSN, he should know. In 1948, he was hired as a regular JPL employee, a Caltech Ph.D. under his belt, one of "Pickering's boys." By 1952, the Korean War was on, and the task of the moment was to design a jam-resistant radio guidance system for communicating with Army/JPL missiles. It was this task that led to the development of "Phase-Locked Loops," which in turn led to Microlock, the Space Ground Link Subsystem (SGLS), the first Coded Doppler Radar and Command system (CODORAC), the Unified S-Band system (USB), the World Wide Network, the Deep Space Instrumentation Facility, and ultimately the system of interplanetary radio guidance that we now know as the Deep Space Network.

No, I did not get all of those systems and their respective acronyms down in my notes. Although I did take copious notes throughout the story, I did so knowing that I would have access to Dr. Rechtin's own notes for the retelling of it. Although greying, I am rather green as a JPLer, after all, and my own Ph.D. is in English, not Engineering. What follows, then, is primarily in Dr. Rechtin's own voice, from his own notes, with some elaboration and emphasis added from the live event.

Techniques available for radio guidance in the early 50s were all based on AM or FM—both highly jammable—or on narrow-band channels with a "low Q" ("Has anyone here even heard of Q?" Rechtin asked, getting some nods). We needed something different, something not so wide open to jamming, particularly for Doppler-producing high-velocity missiles. Then it occurred to us: how much information is there in a missile trajectory after all—100 bits? Why, then, would we want to use then-current multikilocycle AM or FM bandwidths? The bandwidths we would need would be a thousand times smaller than what AM or FM typically used. On the basis of some information theory and thermodynamics, we concluded that what we needed was to build closed-loop feedback systems based on tracking the rapidly changing carrier signal—hence the term "phase lock."

With only a smidgen of understanding of thermodynamics, we leaped to the later validated conclusion that "noise," our greatest barrier to success, was thermodynamic in nature and that trying to find a signal in noise was chasing the wrong objective. Why not try to drive the noise level down, first, say, by using very cool receivers and looking outward into space instead of across or down into a 300-degree earth?

Better yet, why not *use* noise as a signal, Claude Shannon style (as we learned through a Frank Lehan visit there. Indeed, MIT Lincoln Lab was doing just that in a much different application)? Hence "pseudonoise"—a digitally created, absolutely determinate, near-statistical signal using "pseudo"-noise that we produced for both the transmitter and receiver ourselves. With that we had all the essential technology necessary not only for anti-jamming of radio-guided missiles, but for what, about six years later, became the DSN.

Without really trying to, we had completely redefined radio guidance and telecommunications. For these purposes, we had made obsolete such concepts as AM, FM, PM, "Q," noise figure, "hum," and even fixed bandwidths. We added "coded" signals to the vocabulary, the underlying trick to Coded Division Multiple Access (CDMA), the Global Positioning System (GPS), and multiple use of one channel for many signals. We communicated "beneath" the noise. We converted "static" to processed interference. In the process, we converted the infamous "Yellow Peril"—a mathematical treatise hundreds of pages long, authored by Norbert Wiener and published with a yellow cover—into a three-line proof useable for the average Caltech Electrical Engineer.

In 1955, years before JPL was transferred to NASA (without funds, incidentally), we in Walt Victor's CODORAC had nailed down all the essential signal processing techniques needed for interplanetary communications nailed.

But deep space would require still more. It would also need a different kind of ground antenna than had ever been built before — larger, much more precise, much more robust, and much higher frequency. Walt Higa, Bob Stevens, and Bill Merrick not only built the unprecedented DSN antennas, they built them better, under cost, and on time against the unforgiving schedules of the planets. They rewrote the antenna design book to include aerodynamics (not just aerodynamic statics).

The other remaining obstacle, potentially a showstopper for precision orbit determination and guidance technology, was the inherent (uncalibrated) velocity of light in space. Without knowing the velocity of light to better than one part in a million—as Nobel prize winners (in other fields) cheerily pointed out—we could never get close enough to the planets to be any more useful than a ground-based radio telescope. "You guys are just plain nuts," they would say. We would need at least a factor of a million or more

So, in a move that became characteristic of the DSN research, we inverted the problem. Instead of finding out how far away a planet was in meters by using light from the planet and angle measurements, we would measure *time* instead and then guide our spacecraft there by measuring time *differences* between the time it took for a radar to measure the distance to an object and to a spacecraft approaching that object. It is an inherent property of guidance radars that they measure time differences very accurately, regardless of the absolute distance to the target. As we responded to our critics, we didn't care if space were molasses, we could still guide our spacecraft to the planets, once we had measured "radar time" to Venus. In the process of doing research, we dispensed with angle measurements entirely, and we very precisely (one part in 10 to the 15th) calibrated the Astronomical Unit (the average distance between the Earth and the Sun). All this well before MIT, the Russians and the British agreed that their claims to have detected Venus were shown to be untrue.

The special, errorless, technique we had used to send infinitely long pseudonoise signals that could be "cracked" at any time needed. Our critics had said, "You'd have to be geniuses to make that work." But of course we were (the audience concurred, perhaps counting themselves in). So what was the big deal? This concept of using pseudonoise and time differences was critical to GPS. An important recognition in due course came from the National Academy of Engineering when it at different time elected seven of us to membership based on this work from that time at JPL and what followed from it.

One would think that with all this obviously brilliant thinking, all we would need from here on out was a bit of "engineering" and, lo and behold, there would be a Deep Space Network.

The first wake-up call was that the many technologies needed to build, operate, and analyze the performance of spacecraft were yet to be developed. And that would take decades, literally. But the general public wasn't about to wait decades for a response to SPUTNIK. Results *now*. *Beat the Russians now!* was the order of the day. And the DSN couldn't just perform once; it had to keep working. We could not fail. "We will not fail first" became our motto, because if we did, nobody would know what happened thereafter. We could only fail last. In practical terms, the name of *this* game was steady, planable, and *enormous* improvements with time. Unlike many networks, we were not trying to take a single snapshot success. We were about to start (from behind) a race into space that would take at least thirty to forty years before anyone could claim to have "won." The DSN would have to design for continually expanding needs for decades to come. And this is exactly what happened. But it was no happenstance by lucky, if admittedly brilliant people, many of whom are here today.

As part of the original plan (or architecture as we might call it today) we asked NASA for 10% of the annual DSN budget from there on out to fund the DSN research and development. Our model, I am the first to agree, was the Bell Labs. We adapted it because it worked. The DSN was (and is) not one more project, but an evolving, living thing. That's why contracting out the management of the DSN and its research is a flat-out mistake. Contractors are at their best in doing fixed work to a fixed time for a pre-negotiated profit. No contract can capture all the requirements needed for evolving continuously at a predictable rate for decades into the future.

The process of contracting forces both parties to lock in performance cost and schedule that need to change and keep changing far into the future. From the first, we understood that we would need to be able to predict, ten to twelve years ahead, with an uncertainty of plus-or-minus less than one decibel (ten percent, roughly), exactly how well the DSN would deliver the goods to as-yet-undefined projects ten to twelve years in their futures—and keep doing it day after day, month after months indefinitely. I think you can see the direct analogy with the now defunct Bell Labs when they had to do exactly the same think for the now-fractured At&T.

Why for us, in particular? To deliver either more or less than promised would have been equally damaging. The difference, in each direction, would have to be compensated for by basic design changes in the spacecraft. Three decibels meant doubling the affected parts of the design: power, weight, solar panel size, data rates, and so on. Further, not only would it take years for the spacecraft to reach the planets once launched, the basic design parameters would have had to been frozen a decade before that! Hence the justly-famous "Mathison charts" designed and built 40 years ago by the then recently-retired Dick Mathison.

But all this was in the future back in 1958 when the basic structure—what I like to call the "architecture"—of the DSN was being established. This statement begs the question of how to define "architecture."

At this point, Dr. Rechtin pointed to an overhead transparency (reproduced below) listing the features of that architecture. Every item on that list was essential, he began. It's an "architecture" because it all fits together in an interdependent way. You can't just start crossing things off without changing the rest of the tightly-interconnected parts—and hence the overall performance.

The Architecture of the Deep Space Network (and Why)

UNIQUE PURPOSES

COMMUNICATE AND COMMAND to the edge of the solar system
NAVIGATE to the edge of the solar system
SERVE all comers: NASA and other countries
SUPPLY centralized flight operations facility for all projects

DESIGN

Continuous reception and transmission
Plan for the decades
Very low-temperature receivers
Very quiet signal frequencies
Phase modulation of signals
Pseudonoise coding and reception
210-ft diameter, all conditions, antennas
Plan for <10' diameter spacecraft antennas
Plan for low-power (10-W) transmissions only

MANAGEMENT

By JPL DSN and NASA Office of Tracking and Data Acquisition (OTDA) for all comers
Stable R&D by JPL DSN for decades
Continuing prototypes using operational facilities
Interplanetary radar and radio science
20-yr amortization of all facilities
4-year amortization of all electronics
Technical journal with signed reports therein

We recognized early that the only way to accomplish all this would be with remarkable, extraordinarily dedicated people. You didn't come to JPL for the pay (he said, to knowing smiles from the audience). Since we couldn't pay people enough for what we were demanding of them, we acknowledged them by publishing their work in a technical journal (the last item on the slide), *The DSN Report*. Unlike most standard practice in large, "team" organizations, the practice in the DSM had to be that the person who actually did the work should be the one who signs its reports—not the overseeing manage, professor or supervisor.

To accomplish the "Unique Purposes" listed at the top of the slide—communicate and command to the edge of the solar system; navigate to the edge of the solar system; serve all comers, NASA and other countries; and supply a centralized flight operations facility for all projects—we set up a series of 210-foot antenna stations around the globe, each station completely staffed by the hosting country. We wanted people worldwide to know that *they* had built the DSN. Here our model was a typical international airline, the early TWA in particular.

Speaking of the Management issues on the slide, Dr. Rechtin said he was a firm believer in ten-year plans. The predictions for 1958-1968, which he wrote, proved to be good, he said, except where management was concerned.

The DSN has sometimes been faulted for not doing space radar research. (Yet we did and for very good reason—it was and is essential for our mission.) But, how could we do what needed to be done while contending against a specific law that NASA was not allowed to do ground-based research? (As I understand it, the law was demanded by those with an interest in protecting their own interests against the newcomer, NASA.) When you broke you could get thrown in the clink. But to measure planetary atmospheres and so forth, we needed to do just that! The solution? We used operational gear designed for intensive future use, modifying it as needed for our present research purposes (and, of course vice versa but only at very low cost).

And then there was costing. "Costing," Dr. Rechtin pronounced, "means absolutely nothing." (Here he is at least consistent. The same idea appears in his published literature.) He related an anecdote about a congressional staffer who came to his office wanting to know the exact cost of the DSN for the Explorer Project. "Pick a number between zero and infinity" was his reply. There are so many variables involved—how many years the DSN will be in operation, how many missions will use which equipment, how *much* each mission will use it, and over how many years—that it is impossible to put a price tag on it. Evidently the response was satisfactory, it never happened again. Even so, Dr. Rechtin said, "I soon had a reputation for always having money." Part of that comes from his belief that there is no such thing as cutting reasonable costs, only redistributing them.

Back to the slide which never left the screen throughout the story telling.

That slide, he said, of the slide he was just then removing from the projector, is what we hoped and architected for the DSN into the indefinite future. This, he said, as he put up the slide reproduced below, is what seems to have happened in the 40+ years since.

The Architecture of the Deep Space Network (Now)

~~UNIQUE~~ PURPOSES

COMMUNICATE to the edge of the solar system
NAVIGATE to the edge of the solar system
~~SERVE all comers: NASA and other countries~~
~~SUPPLY centralized flight operations facility for all projects~~

DESIGN

~~Continuous reception and transmission~~
~~Plan for the decades~~
Very low-temperature receivers
Very quiet signal frequencies
Phase modulation of signals
Pseudonoise coding and reception
210-ft diameter, full coverage, ground antennas
Plan for <10' diameter spacecraft antennas
Plan for low-power (10-W) transmissions only

MANAGEMENT

~~By JPL DSN for all comers~~
~~Stable R&D by JPL DSN for decades~~
Continuing prototypes using operational facilities
~~Interplanetary radar and radio science~~
~~20-yr amortization of all facilities~~
~~4 year amortization of all electronics~~
Technical journal with signed reports therein

Pointing to the losses represented by the strikethrough type above, Dr. Rechtin first and intensely regretted that the DSN's purposes are no longer unique. The French and Italians now have their own systems for exploring Mars. A big cost associated with recent "faster, better, cheaper" policies, he said, is that we no longer serve the whole world— we have lost the monopoly over deep space communications that we had held for over forty years. Low-orbit satellite relays around Mars cannot provide continuous reception and transmission. They can't listen continuously, so you very seldom know what's happening on the far side of a planet. And because of the loss of monopoly, we can no longer plan reliably for the decades. Reluctantly climbing onto what he admitted to be his "hobby horse", Dr. Rechtin openly lamented that JPL no longer managed, much less architected the DSN.

On a more positive note, however, he put up a third transparency (below), listing all of the unplanned and unexpected accomplishments of the DSN over the years—calibrating the Astronomical Unit, for instance, as mentioned above, and rescuing legally dead spacecraft by reprogramming them in space—essentially teaching them to "change their minds" mid-mission! These and other such bonuses have been as welcome as unexpected.

Unplanned and Unexpected Accomplishments

Calibration of the Astronomical Unit
Emergency spacecraft operations
Near-simultaneous US/Soviet service
Very close timing of Block IV implementation
In-flight network upgrades
Multiple (and higher) operating frequencies
Addition of special purpose ground antennas
Arrays of antennas for signal enhancement
Use of extremely stable clocks for new spacecraft capabilities
Determination of characteristics and composition of planetary atmospheres
Precision determination of intraplanetary system orbits
Color pictures of planets and their moons

Finally, Dr. Rechtin wrapped up with the slide below, detailing the glowing assessment of the DSN by highly honored Caltech scientist Lee Dubridge (Caltech President during the development of the DSN, and subsequently Science Advisor to President Nixon). In Dubridge's assessment, the DSN is "the sole development that made the in situ exploration of the solar system possible."

Lee Dubridge's Assessment of the Role of the DSN

The DSN is the sole development that made the in situ exploration of the solar system possible.

Sensitivity: a factor of a million
Reliability: never failed a mission in 30 years
Precision: a factor of a million
Timeliness: never late
Cost: on budget every year to within 1%; met every target cost for antennas, operations
Predictability: within 1 dB ten years or more in advance; 10-year plans

Research and development: maser, antenna design, communications parameters, uncrackable codes; quick cracking of "infinitely long" pseudonoise strings

Deliberately dropped certain lines of research: angle measurements, laser transmission through space, ionospheric transmission

Encouraged and funded other critical lines of research: Higa and Townes, Golomb, Welch, etc.

50 years of technical journal signed research

The audience was invited to ask questions, many of which centered on strategic thinking for the exploration of the planets. One heady discussion concerned the prospect of sending geosynchronous relay satellites to Mars (maybe funded by Hughes, Direct TV, or—why not?—Mars Bars) so that spacecraft exploring the planet wouldn't have to turn to Earth every time they wanted to communicate. They would only have to communicate with these satellites.

It was a discussion that no one wanted to end. Indeed, it continued for some time well after Teresa officially closed this session of the JPL Stories by presenting Dr. Rechtin with a small, crystal globe that has become the customary gift for recognizing the jewels of insight brought to us by our storytellers.

A postscript

In his notes, Dr. Rechtin concludes with a meditation—implicit in his story, though mostly unspoken—on insight, architecture, and the relationship between them. It seems fitting to end this story *about* the story by giving him the last word.

"Architecture" (he begins) is a strange and wonderful thing, and has been since its initiation by the Egyptians 5000 years ago. Architects are less interested in what's elegant than in what works. Architecting is driven by purpose; that is, answers to the questions of why you want to build this thing at all and with what. Such questions are not easy to answer. The answers change with time, circumstance, and stakeholders. Engineers might attempt to create a systems architecture by the classic paradigm: generate options and optimize to get the best. In many cases, this works. But where did the options come from, and what does "best" mean to a diverse group of stakeholders? The answer may surprise some of you: By insight.

As one such insight goes, "A picture may be worth a thousand words, but an insight is worth a thousand analyses."

Resources for Further Exploration:

Deep Space Network Home Page:
http://eis-fil-www03.jpl.nasa.gov/deepspace/dsn/index.html

Deep Space Network Brochure:
http://deepspace.jpl.nasa.gov/dsn/brochure/index.html

IEEE Oral History Interview of Eberhardt Rechtin by Frederick Nebeker:
http://swww2.ieee.org/organizations/history_center/oral_histories/transcripts/rechtin.html