Case Study in System of Systems Engineering: NASA's Advanced Communications Technology Satellite

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Abstract - *System of systems (SoS) systems engineering (SE) (SoSE) has become an important and popular topic during the past several years. Those familiar with the concepts and principles of complex SE (CSE) and Enterprise SE (ESE) recognize that SoSE engineering comprise special instances. All these forms of SE can be usefully illuminated by cogent case studies. Unfortunately, technology still seems to be the primary focus in many SE efforts, particularly those involving SoSs. This was true during NASA's past Advanced Communications Technology Satellite (ACTS) program. The goal of this case study is to show how well some non-technologically-focused CSE and ESE ideas worked on the ACTS program, even then.*

Keywords: ACTS, complex systems engineering, CSE, enterprise systems engineering, ESE, NASA, SE, SoS, systems engineering, system of systems.

1 Introduction

Four types of SoSs have been proposed, Virtual, Collaborative, Acknowledged, and Directed, in order of decreasing complexity [1]. ACTS was of the most benign type, a Directed SoS, managed solely by the NASA Lewis Research Center (LeRC) in Cleveland, OH; in 1999 this became the Glenn Research Center (GRC)[1] in honor of former U.S. Senator and famous astronaut John H. Glenn.[2]

1.1 ACTS

ACTS was an advanced domestic communications satellite system that explored modern on-board processing, multiple hopping-beam antenna techniques, and related technologies. ACTS operated at Extremely High Frequency (EHF) in the 30/20 GHz uplink/downlink frequency bands. These capabilities facilitated widespread experimentation involving many different types of users and earth terminals.

ACTS began with extensive theoretical studies by technical staff (including the authors) at MITRE in Bedford, MA, from 1979 to 1981. Much of this paper is a reflection of that personal experience. The ACTS satellite was launched in 1993 as the result of a successful decade of collaboration between NASA and industry.

In 2000 after six years of innovative experimentation, and near the end useful life, the satellite was reconfigured through orbital changes to extend its operation. The ACTS program received several prestigious awards between 1997 and 2002. The satellite continued to be utilized for educational purposes. In 2004 the satellite was shut down.

The initial and ultimate system environments [2] and SE activities [3] of ACTS, as characterized by the first author were completed during preparation of this paper. However, because of page and space limitations, they will not be included here.[3] Instead, priority has been given to explaining the SoSE principles listed in Sec. 1.2 below.

1.2 SoS Engineering Process Definition

Suggested elements of a model SoSE process can be characterized by the thirteen principles listed below. [4] [5] As will be seen by citation in later examples, most of these (all but Principles 4 and 8) were applied to good effect within the ACTS program.

1. Bring a healthy dose of personal humility when trying to solve real-world problems.
2. Follow a holistic approach focused on the entire system and the relationships: a) between the system and its environment; and b) internal interactions.
3. Balance competing interests across the system instead of trying to optimize any of its components.
4. Utilize trans-disciplinary techniques of philosophy [6], psychology, sociology, organizational change theory, etc.
5. Consider political (P), operational (O), economic (E), as well as [technology] (T) factors.
6. Nurture discussions to learn how people express their concepts using different terms.
7. Pursue opportunity as well as risk management.
8. Formulate heuristics (<u>practical</u> rules of thumb) and educate emotions [7] to assist decision makers.

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[3] The first author plans to present characterizations of the before-and-after ACTS systems environment and SE activities in this paper's conference presentation. Feel free to contact him for a copy of the presentation.

9. Foster interpersonal and inter-organizational trust by sharing information with honesty and integrity.
10. Create environments (as a governor, leader, or manager) for interactions of all system elements.
11. Stimulate a system of self-adaptation and self-organization to enable, evolve, and accommodate change through competition and collaboration.
12. Design, formulate, and certify simple elements.
13. Develop open, layered architectures well-matched to networks of tightly-coupled, highly-interactive elements within each sub-network, and "loose" inter-connections among the sub-networks.

The above-listed principles will be explained to some extent below (but not in numerical order) in telling short stories about how they applied on ACTS. Caveat: Our principles should not be considered a complete set; other new or related CSE principles may be devised as one learns how to deal more effectively with complex systems, enterprises, and SoS. These principles reflect a general view of SE that introduces new techniques, while not being wedded to conventional methods (such as reductionism) that do not always work well with complex systems.

2 Background

The aforementioned MITRE studies examined appropriate techniques and critical technologies for the expected demand for domestic wideband trunking and direct-to-user services in the 1990s.

2.1 Context

Technical requirements entailed interconnecting tens of Mb/s data rate digital trunks emanating from 40 million-people-plus, metropolitan centers, as well as several Mb/s-each, user-user channels, all within the U.S. A non-uniform distribution of communication traffic had to be handled.

A near-geostationary satellite was assumed. Tens of simultaneous beam-hopping (or scanning) and high-gain satellite antennas for efficient reuse of the 2.5 GHz wide (K_a-band) allocations were needed, along with an on-board microwave switch with tens of input/output ports. An all-digital on-board processor for demodulation/decoding, baseband switching, and recoding/remodulation with GHz-speed logic and Mb of memory was also necessary.

Principle 1 (of Sec. 1.2 above) certainly applied in facing this daunting task! Many people involved with the formulation, management, and systems engineering of government acquisition programs seem to believe—or at least feel—they are in control of every difficult situation. Accordingly, the traditional tendency is to try to instigate success in a command-and-control fashion from their perch at the top of their (usually hierarchical) organization. Fortunately, LeRC management adopted a more appropriate attitude: They were suitably humble in

approaching the ACTS problem. Instead of a rigid, know-it-all management style, they created an atmosphere that readily facilitated inputs and fresh ideas from others. This eventually led to a more effective and lasting solution.

Principle 5 also was huge. Although the technical thrust was focused on K_a-band technology, political, operational, and economic aspects were equally important. The political objectives included advancing U. S. prestige in space programs in general, and satellite communications in particular, especially considering increasing competition from the European Space Agency. We also wanted to help demonstrate the practical operational use of the K_a-band, a relatively unexploited portion of the available spectrum. Finally, these capabilities had to be affordable, so the economic piece of the puzzle needed to mesh, as well.

2.2 Definitions

Conveying a description and understanding of a host of technical concepts and terms was helpful to the LeRC program manager and staff during the study contract. The MITRE team (led by the late William T. Brandon) utilized many face-to-face meetings with NASA to accomplish this objective. Here Principle 6 applied.

Quite often professionals argue vehemently about definitions, trying to get each other to agree on their particular expressions of common ideas. This is often counterproductive because of ensuing delays in solving the real problems. A mutual understanding of how we use words and a tolerance for different definitions is what is important, as long as these variants do not hinder progress.

A model of the initial on-board processing satellite architecture postulated is shown in Fig. 1. Technical definitions associated with this model (themselves omitted because all the terms are so well known within the communications and networking community) were provided. Near the beginning of the LeRC contract MITRE explained its SE process and methodology.

In response to a rash promise to the LeRC to consider all possible" (!) on-board processing designs, a decision tree structure was devised by the first author to bring some sanity to the discussion. Considering a number of reasonable alternatives, more than 92,640 options were shown to be possible. For various reasons, only 44 of these were taken seriously. But even 44 architectural alternatives were too many to be adequately treated, so only the most viable ones were selected for elaboration. The relative merits of fixed or scanning beams, FDMA or TDMA, circuit or packet switching, QPSK or MSK, IF switching, and baseband regeneration were emphasized.
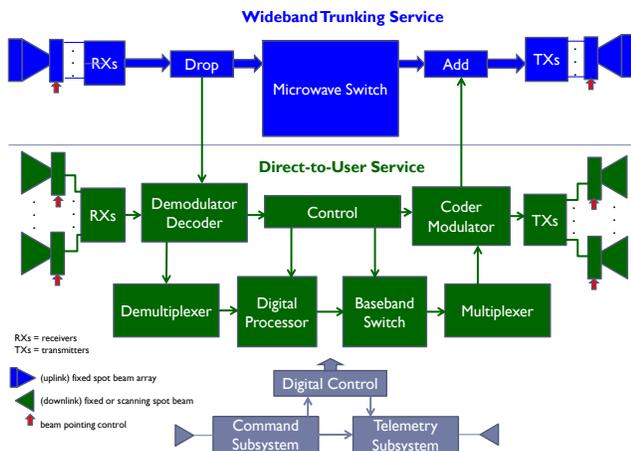
Figure 1. Initial On-Board Processing Satellite Architecture

2.3 Relevant Theories

The system alternatives alluded to in Sec. 2.2 were considered, largely following Principle 2. This contrasts with the more common approach of separating a complex system to its constituent parts, trying to optimize each sub-system as if it is frozen in time, and then recomposing the result. As already mentioned this (reductionism) does not work well because many things (e.g., the politics, the requirements and the system environment) may have changed in the meantime. All alternatives were backed by significant theories. Some of these are described below.

2.4 Prior Research

The most relevant areas espoused in the first phase of the study (and the reasons why) are cited below:

1. Shannon's channel capacity (R_o)—fundamental to the ultimate limits of coding theory for discrete memory-less communication channels [8]
2. Viterbi's efficient maximum-likelihood decoding algorithm—a very practical scheme [9] [10]
3. Bandwidth-Power efficiency tradeoffs—to select a modulation with high b/s/Hz and low E_b/N_o, i.e., for a given data bit error rate (BER), a high data (throughput) rate to spectral bandwidth consumed, and low energy per (data) bit per (white Gaussian, single-sided) noise power spectral density [11]
4. Bandwidth efficient modulation—for low cross-talk satellite uplinks [12] [13]
5. Demand assignment multiple access—for more efficient use of communications channels under moderate and varying traffic loadings
6. Multiple beam optimizations—the first author's extensive analysis of the parametric relationships among 20 variables to establish many effective system design points for fixed and scanning beams on uplinks and downlinks, on-board IF switching or regeneration (for e.g., FDMA uplinks and TDM downlinks), assuming various numbers of users of

T1, T2, T3, and T4 Carrier traffic, and total satellite (2.5 GHz) bandwidth, etc.
7. Large (e.g., 100×100) IF (2-4 GHz frequency) switches—knowledgeable experts of a dozen U.S. organizations were contacted to gather advice and to ascertain what technical obstacles might impede development; in conjunction with a thorough literature review many detailed designs covering several feasible technologies and switch configurations were studied and evaluated by MITRE's Murray Hoffman.

In sorting through which of these research areas were crucial for ACTS, Principle 3 was applied to ensure that the main goals of both wideband trunking and direct-to-user service were aptly accomplished with innovative technology and demonstrations to motivate follow-on refinements and later potential optimizations. Areas 3, 4, 6, and 7 were deemed most important.

3 SoS Description

Three systems are described in this section. The first two were due to MITRE's SE study efforts. The third reflected industry efforts resulting in the ACTS realization.

3.1 History and Development

In the first year of study, an initial on-board processing definition was completed by a project team led by the second author (in May 1980). This (hybrid) design recommendation consisted of a TDMA uplink, an on-board IF switch, and a TDM downlink for the trunking channels; and uplink FDMA, on-board baseband processing, and downlink TDM for the direct-to-user Customer Premises Service (CPS). For the purpose of descriptions in following sub-sections, this design is called SoS I.

At that time there was a preponderance of contractor studies and proposals and common-carrier sentiment for an all TDMA/TDM implementation. This was due mainly to the NASA's very ambitious traffic model which included many postulated users/cities with very high data rates. The prevailing opinion was that TDMA could provide these services more efficiently than FDMA, at least from a satellite perspective. However, this implied that earth terminals would need orders-of-magnitude larger burst rates, a feature requiring much higher transmitter power, sophisticated synchronization techniques, and therefore a significant increase in terminal cost. Only General Electric's Space Systems Division had advocated an all FDM concept, albeit for much lower data rate terminals. Therefore, during the second year of study effort the LeRC asked MITRE for an independent opinion on the feasibility of an FDMA/FDM system. This presented a great opportunity for innovation while challenging us to be mindful of the relative risks of such a radically different systems approach, i.e., Principle 7 was exercised. Thus, FDMA uplink, no on-board baseband processing, and FDM

downlink alternatives were examined in detail (in a May 1981 report). An exemplar FDMA/FDM version from this study is called SoS II.

In preparation for this effort, MITRE visited GE to learn more about their FDM approach and to interchange technical ideas. This interaction among companies was encouraged by the LeRC and is one example instance where Principle 10 certainly applied.

The next few years at the LeRC were consumed by contemplating MITRE's study results and bringing on private industry. In 1984 a contract was awarded to

- RCA Astro, East Windsor, NJ

(which ultimately became part of Lockheed Martin)
—system integration and spacecraft bus
The initial industry team also included

- TRW, Redondo Beach, CA
—spacecraft communications payload
- COMSAT Laboratories, Clarksburg, MD
—network control and master ground station
- Motorola, Chandler, AZ
—baseband processor
- Electromagnetic Sciences, Norcross, GA
—spot-beam forming networks.

In 1988 Lockheed Martin assumed development of the communications payload, and later (after becoming General Electric Astro Space) subcontracted with

- Composite Optics, Inc., San Diego, CA
—manufacture of antenna reflectors and part of bus structure. [14]

The ACTS version launched in 1993 [15] is called SoS III.

Throughout the '80s and early '90s, the LeRC exemplified Principle 9, making collegial friends with all the contractors, starting with MITRE. They kept us informed about program status, how their thinking was evolving, and inspired a continual focus on good planning.

For more than six years, ACTS was used as a "Switch-board in the Sky" testbed for terrestrially-initiated experiments (using a variety of more than 50 special ground terminals and 100 experimenters), in fields of, e.g.,

- Computer networking
- Telemedicine
- Petroleum (industry)
- Education
- Defense (Army deployment in Haiti; ships at sea)
- Business (interconnecting bank offices; public switched network restoral; meteorological and marine forecasting, linking Keck telescope and Califormia Institute of Technology; expanding Internet)
- Emergency response
- Mobile communications
- Astronomy. [16]

Experiments continued until 2000. From 2001 to 2004 ACTS was used for educational research. [17]

3.2   High-Level Diagram or Layout

The design of SoS I (refer to Fig. 2) assumed channel availabilities of 99.99% and 99.9%, respectively, for 40 trunking and 2000-5000 CPS terminals. To compensate for rain attenuation effects, dual (spatial) diversity trunking terminals were proposed. For those CPS terminals without access to local switching centers, 96.8% channel availability was assumed acceptable.
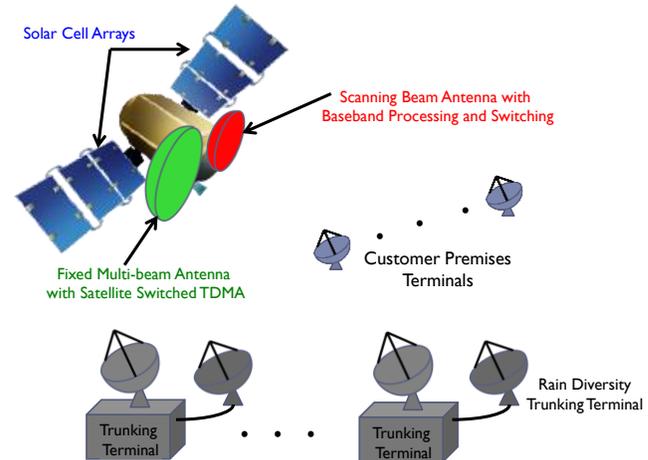

Figure 2. Exemplar Concept of SoS I

In the spirit of Principle 7, as alluded to above, a frequency-routed satellite concept, SoS II, offering orthogonally-polarized beams for frequency reuse, was thoroughly explored. This became a competitive alternative to SoS I which employed a common IF, a large microwave switch, many down-converters and up-converters, and a synthesizer that had to generate a different local oscillator frequency for every converter. In SoS II, an innovative notion of beam groups simplified the satellite transponder design. A simple beam and frequency plan illustrating the basic concept is shown in Fig. 3. This was a primary example of Principle 12, where fresh thinking about basic elements generated an entirely different but reasonably attractive system alternative. Realistic traffic matrices, beam and frequency plans, and transponder designs are available in [18] and [19].

A rough sketch of the Switchboard in the Sky (SoS III) is depicted in Fig. 4 [16]. This was the first high-speed (billions of bits per second), all-digital, telephone-system-type switching communications satellite. It operated in geosynchronous (23,300 miles above the equator) earth orbit at 100 degrees West longitude, and weighed 3250 pounds at the beginning of its on-orbit life.
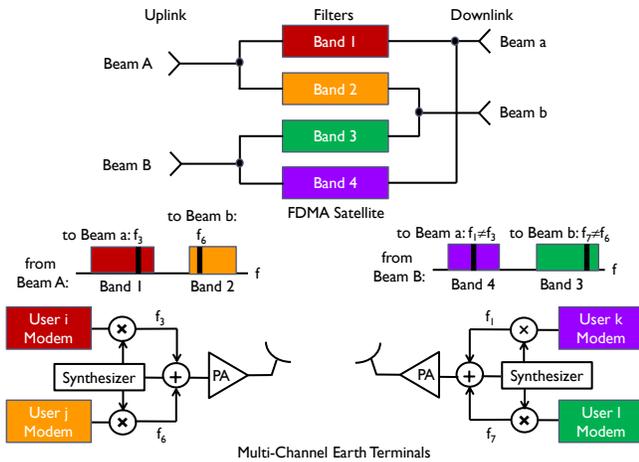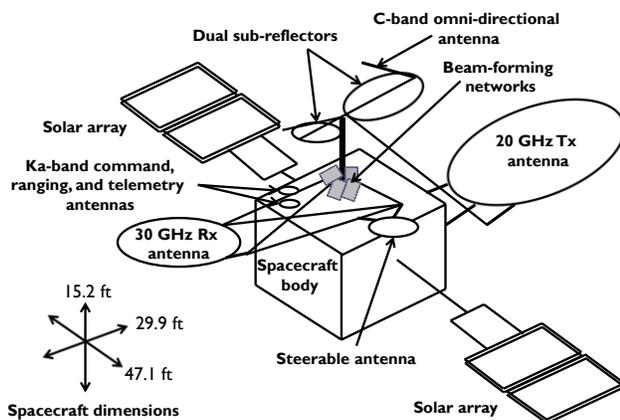
Figure 3. Satellite-Routed FDMA Concept of SoS II

Figure 4. ACTS of SoS III

3.3 Sponsor, Industry, Country, Budget

As stated in Sec. 1, NASA was the sponsor. Industry partners are listed in Sec. 3.1. Some high-level information provided in [20] indicates that in 1988 the ACTS budget was capped at $499M by Congress. However, the MITRE study portion of the effort lasted only 2 years and consumed only about six full-time-equivalent staff years per year.

3.4 Mission/Purpose/Goal/Objective

NASA's overarching aspirations [16] were to help: 1) realize what later became known as the information "super highway" in space, something that had already started on the ground with the advent of the Internet and research into optical fiber communications, for example; 2) make space technological breakthroughs in the K and K_a-band; 3) create opportunities for commercial U.S. companies to improve their services by greatly increasing communication capacities; and 4) protect and further ensure the then perceived U. S. lead in the world's satellite communications.

3.5 Principles/Characteristics

The LeRC "led the charge" embracing and applying many SoSE principles listed in Sec. 1.2 in employing the overall precept of openness (embodied in Principles 1-3, 5-7, 9-10, 12, and as noted below, 11 and 13). They always welcomed new ideas and ever sought information that would further the cause. In particular, Joseph (Joe) N. Sivo, chief of the Communications and Applications division (and "Father of ACTS") [20] at the onset of the effort, and Richard T. Gedney, the ACTS project manager from 1980 to 1995 [21], strongly embodied this entrepreneurial spirit.

3.6 Settings/Structure/Boundaries

As described in Sec. 1 ACTS was a Directed SoS. The responsibilities distributed among the major organizational and interacting components are suggested by Fig. 5. A clockwise time progression from "NASA" is intended with "FFRDC" essentially dropping out after the study phase.
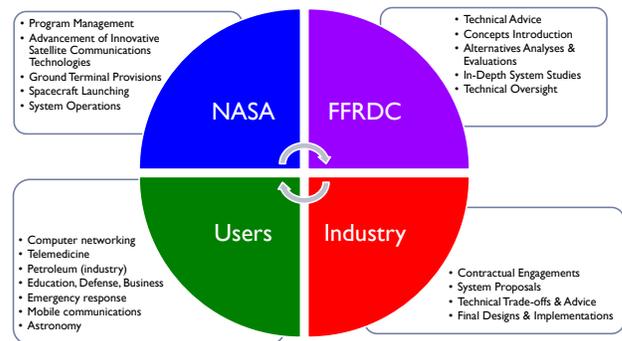

Figure 5. ACTS Relationships and Responsibilities

3.7 External Factors and Constraints

Limitations of K_a-band technology (primarily maturity and cost) were the driving factors but also the prime motivations for ACTS. Competition with EHF military satellite communications efforts in the form of the Military Strategic and Tactical Relay (MILSTAR) satellite program was tangible.

3.8 Constituents (new/legacy, scope)

Considerable opportunities for fertilization between ACTS and MILSTAR became possible since Lockheed Martin was the prime contractor on both programs. Each benefited from the other through the complex systems Principle 11 of continual collaboration and competition.

4   SoS Engineering Analysis

A summary and sampling of the outcomes of each system's engineering analyses are provided here.

4.1   Analysis and Analytical Findings

What was purported to be a "minimum cost" SoS I design is provided in Table 1 [22].

Table 1. SoS I Characteristics

Item	Trunking Channel	Customer Premises Channel
No. Satellite Beams	40 fixed	2 scanning
Modulation	DQPSK* (up/down)	DQPSK/CQPSK**
Access (uplink/downlink)	TDMA/TDM	FDMA/TDM
Bandwidth/Beam	2400 MHz	100 MHz
Data Rate/Beam	3300 Mb/s	150 Mb/s
Sat. Ant. Dia. (30/20 GHz)	3.4/5.1 m	1.5/2.3 m
Terminal Ant. Diameter	7.3 m	1 m
Terminal RF*** power	30 W	6 W
No. Terminals	80	5000
Total Terminal Cost	$87 M	$505 M
Item	Value	N/A
Satellite Weight	5200 lb	
Satellite Power	2630 W	
Satellite Cost	$89 M	
Non-Recurring Engineering Cost	$300 M	
Total Cost	$981 M	

* Differential Quadrature Phase Shift Keying	** Compatible differential offset QPSK	*** Radio Frequency

An in-depth study focused on baseband processing was completed (in October 1980). The most significant finding was that with circa 1980 state-of-the-art device technology, the prospects for handling a bandwidth much more than 100 MHz was quite unlikely! Consequently, this study assumed a system design perturbation of 8 fixed and 8 scanning beams on both uplinks and downlinks each utilizing the same 100 MHz for CPS. A deep investigation into the topic of channel access and routing/switching protocols was also included. The recommended design resulted in a total 1.6 Gb/s throughput, assuming 1b/s/Hz modulation efficiency, and a very detailed but feasible baseband processor example realization.

Fig. 6 represents SoS II, one of several Satellite-Routed (SR)—FDMA alternatives studied as performance and cost competitors of Satellite-Switched (SS)—TDMA systems. The regional concept is unique in greatly reducing the number of filters, amplifiers, and IF converters.

This contiguous U. S. (CONUS) map projection was chosen to show sub-satellite beams as circles; this makes inter-beam isolations easier to analyze [19]. In Fig. 6, CPS occupies the spectral segments indicated by the clear or lined pattern in the upper portion of each beam footprint, corresponding to the left-hand 1.7 GHz of the 2.5 GHz spectrum allocation. Trunking service utilized the spectral
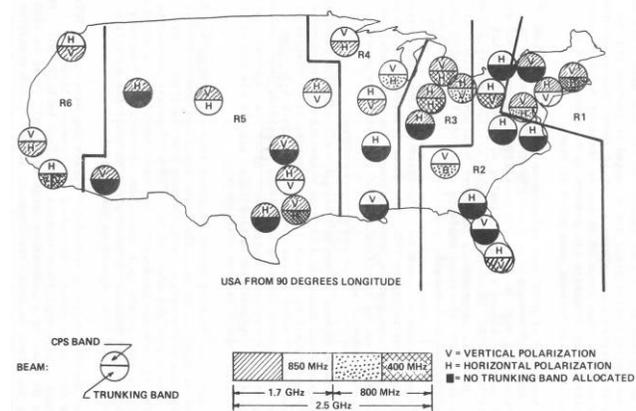

Figure 6. Beam Plans for Six-Region SoS II[4]

segments indicated by the dotted or cross-hatched pattern in the lower portions of each beam footprint, corresponding to the right-hand 800 MHz of spectrum. Vertical (V) or Horizontal (H) beam polarizations are also indicated.

SoS III's analysis and analytical findings resulted in the actual ACTS which included 5 simultaneous, scanning, spot-beams that could cover 51 CONUS locations [23]. Each beam footprint had a diameter of 150 to 200 miles. The beams "hopped" from location to location in less than 1 microsecond. An on-board baseband processor provided spot-beam data interconnections. The microwave switch interconnected fixed beam traffic using three 900 MHz-wide transponders each supporting 622 Mb/s. [16]

Principle 13 was present in all three SoS concepts presented here. Each of the wideband and narrowband networks for trunking service and CPS, respectively, were strongly interconnected. However, these networks, through being implemented on the same satellite, were only loosely connected with each other.

4.1.1   Activities/Problems/Conflicts

There were a few inter-personnel issues that developed among the MITRE staff during the study effort but happily these were resolved with only positive impacts on the technical work.

There were some MITRE inter-team rivalries that aligned with different approaches to solving SoS I and II problems. But again, the team and the study products benefited from this competition and collaboration.

4.1.2   Timeframe/Sequence of Events

At this time NASA was again flexing its muscles in refining Space Shuttle design and launching experimental Shuttle flights. Now that this major new mission thrust was underway, they were also rethinking their "roles and

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[4] We suggest viewing this figure with a 200% scale for better readability.

missions" alternatives. Hence their foray into advanced space communications technology and applications.

4.1.3 Methods and Tools Used

The specific session focus topic of SoS did not exist during this (SoS) effort and prior to the launch of ACTS in 1993; Wikipedia's first reference to SoS is dated 1996.

During the MITRE study, several tools and models were used. As already mentioned, fundamental use was made of NASA's data traffic model.

The MITRE Interactive Communications Analysis Program (MICAP) was used to analyze satellite system communications alternatives, including satellite and terminal costs. This software program was developed by MITRE's Dr. John Ruddy and Daniel Fritz. MICAP was run on MITRE's IBM 370 mainframe from office workstations.

Various propagation perturbation effects on EHF communications links utilizing rain attenuation models were exercised. MILSATCOM Program Office cost models were also employed.

4.2 Lessons Learned

The recommendations of the MITRE studies were too ambitious considering the relatively modest capability ultimately implemented. For example, ACTS evidently included only a 3×3 IF switch, whereas MITRE had investigated a 100×100 switch in great detail. Furthermore, ACTS also included only 5 scanning beams whereas the MITRE studies had assumed up to 40 fixed beams and 2-8 scanning beams. Sometimes simpler but less capable solutions sit better with the customer, especially considering ultimate system cost as an independent variable!

4.3 Best Practices

Thorough investigations of many SoS alternatives and technical issues and close attention to detail characterized the MITRE studies. The LeRC was faithful to potential users, not only in generating the traffic model but also in providing experimentation terminals. The LeRC also listened to industry and utilized their technical inputs.

4.4 Steps and Conditions for Replicating the SoS Elsewhere

Being an old program the replication of ACTS itself is not applicable. However, the methodology used by NASA LeRC in investigating and developing new technology demonstrations that significantly advance the state-of-the-practice is certainly still worth pursuing.

5 Conclusion

ACTS was highly successful in that: 1) a thorough study of system alternatives benefited the final design; 2) many highly competent industrial contractors incorporated modern K-Band technology into the satellite; and 3) useful experiments for broad classes of users advanced the state-of-the-art in practical ways. It is apparent that many CSE principles were at play, even before their formalization, in a "doing while thinking" SE philosophy [6, p. 63].

Principles 4 and 8 were not in much evidence during this study. This is quite understandable because (referring to Principle 4) the soft sciences have become much more relevant in recent years as important aspects of dealing with complex systems. It's much more about people now, as opposed to just technology. Also, (referring to Principle 8) we are learning that decision making is often highly dependent upon our sub-conscious, our emotions, and not purely about gathering all the facts and applying just rational thought [7]. Maier and Rechtin [24] is a great source on the topic of decision-making heuristics.

6 Questions for Discussion

1. How much has the Internet and the advent of social networking obviated the communications objectives of the ACTS Program? What are the fundamental reasons for this?

2. What collaborative effort between Government and Industry would you foresee and recommend to advance what technologies today? To what extent would/could FFRDCs and NASA be players?

3. What needs to happen in the SE realm to help assure successful future ventures of this sort?

Dedication

This paper is dedicated to the memory of William T. Brandon, the MITRE Project Leader of the ACTS study effort, who died suddenly in Concord, MA, on 13 November 2005. Consistent with his long and distinguished career, he was magnificent in leading the MITRE team and interfacing with the NASA LeRC customer.

References

[1] J. S. Dahmann, G. Rebovich, Jr. and J. A. Lane, "Systems Engineering for Capabilities," *CrossTalk (The Journal of Defense Software Engineering)*, Vol. 21, pp. 4-9, November 2008.

[2] R. Stevens, "Profiling Complex Systems," IEEE Systems Conference, Montreal, Quebec, Canada, 7-10 April 2008.

[3] B. E. White, "Systems Engineering Activity (SEA) Profiler," CSER, Hoboken, NJ, 17-19 March 2010.

[4] B. E. White, "Personal History in System of Systems," Special Session on System of Systems (SoS), International Congress on Ultra Modern Telecommunications and Control Systems, ICUMT-2010, Moscow, Russia, 18-20 October 2010.

[5] B. E. White, "Managing Uncertainty in Dating and Other Complex Systems," CSER, Redondo Beach, CA, 15-16 April 2011.

[6] J. Boardman and B. Sauser, *Systems Thinking—Coping with 21st Century Problems*, CRC Press, Boca Raton, FL, 2008.

[7] D. Brooks, *The Social Animal—The Hidden Sources of Love, Character, and Achievement*, Random House, New York, 2011.

[8] R. G. Gallager, "A Simple Derivation of the Coding Theorem and Some Applications," *IEEE Transactions on Information Theory*, Vol. IT-11, No. 1, January 1965, pp. 3-18.

[9] A. J. Viterbi, "Error Bounds for Convolutional Codes and an Asymptotically Optimum Decoding Algorithm," *IEEE Transactions on Information Theory*, Vol. IT-13, No. 2, April 1976, pp. 260-269.

[10] G. D. Forney, Jr., "The Viterbi Algorithm," *Proceedings of the IEEE*, Vol. 61, No. 3, March 1973, pp. 268-278.

[11] T. A. Schonhoff, "Bandwidth vs. Performance Considerations for CPFSK," Proceedings National Telecommunications Conference, New Orleans, LA, 1-3 December 1975, pp. 38-1―38-5.

[12] B. Reiffen and B. E. White, "On Low Crosstalk Data Communication and Its Realization by Continuous-Frequency Modulation Schemes," *IEEE Transactions on Communications*, Vol. COM-26, No. 1, January 1978, pp. 131-135.

[13] I. Kalet and B. E. White, "Suboptimal Continuous Shift Keyed (CSK) Demodulation for the Efficient Implementation of Low Crosstalk Data Communication," *IEEE Transactions on Communications*, Vol. COM-25, No. 9, September 1977, pp. 1037-1041.

[14] Advanced Communications Technology Satellite (ACTS), About ACTS, History, Program Beginnings, http://acts.grc.nasa.gov/about/history.shtml.

[15] Advanced Communications Technology Satellite (ACTS), About ACTS, History, Launch and Orbit, http://acts.grc.nasa.gov/about/history.shtml.

[16] "Switchboard in the Sky―The Advanced Communications Technology Satellite (ACTS)," FS-2002-06-013-GRC, NASA Facts, National Aeronautics and Space Administration, Glenn Research Center, June 2001, http://www.nasa.gov/centers/glenn/pdf/84798main_fs13grc.pdf.

[17] Advanced Communications Technology Satellite (ACTS), About ACTS, History, Experiments, http://acts.grc.nasa.gov/about/history.shtml.

[18] G. Berk, P. N. Jean, E. Rotholz, and B. E. White, "A Frequency-Division Multiple-Access System Concept for 30/20 GHz High-Capacity Domestic Satellite Service," *Journal of Spacecraft and Rockets*, Vol. 20, No. 6, November-December 1983, pp. 619-625.

[19] E. Rotholz and B. E. White, "A Frequency-Routed Satellite System Concept Using Multiple Orthogonally-Polarized Beams for Frequency Reuse," IEEE MILCOM '83, Arlington, VA, 31 October 1983.

[20] "Flight System Definition Studies," excerpt from *The Advanced Communications Technology Satellite*, R. Gedney, R. Schertler and F. Gargione, SciTech Publishing, Inc., Mendham, NJ. 2000, http://spacejournal.ohio.edu/issue2/program2.html.

[21] D. A. Day, "Footnotes of shuttle history: the Advanced Communications Technology Satellite," *The Space Review*, 17 January 2011, http://www.thespacereview.com/article/1757/1.

[22] J. M. Ruddy and B. E. White, "Application of Advanced On-Board Processing to Satellite Communications―Cost/Performance Implications for Technology Development," International Telemetering Conference (ITC '80), San Diego, CA, 14-16 October, 1980.

[23] Advanced Communications Technology Satellite (ACTS), About ACTS, Operations, Antenna coverage, http://acts.grc.nasa.gov/about/operations/index.shtml.

[24] Mark W. Maier and Eberhardt Rechtin, *The Art of System Architecting*, Appendix A, Third Edition, CRC Press, Boca Raton, FL, 2009, pp. 395-408.