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

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CAU↔SES (“Complexity Are Us” ↔ Systems Engineering Strategies)
Outline of Talk

- Introduction
- Profilers
- Principles
- The Problem
- System Designs
- The Results
Purpose
- Explored on-board processing, fixed/hopping-beam antennas, and μwave switch
- Operated at Extremely High Frequency (EHF) in 30/20 GHz bands
- Facilitated widespread experimentation with many users and earth terminals

History
- Began with studies by MITRE from 1979 to 1981
- Satellite launched in 1993 after successful collaboration with industry
- Six years of innovative experimentation
- Program received awards between 1997 and 2002
- Satellite continued to be used for education.
- Satellite was shut down in 2004

SoSE Characterizations
- System environments and SE activities are characterized in next two charts
Enterprise Systems Engineering (ESE) Profiler

- **Traditional program domain**
  - Well-bounded problem
  - Predictable behavior
  - Stable environment

- **Transitional domain**
  - Systems engineering across boundaries
  - Influence vs. authority

- **Messy frontier**
  - Political engineering (power, control...)
  - High risk, potentially high reward
  - Foster cooperative behavior
Systems Engineering Activities (SEA) Profiler

<table>
<thead>
<tr>
<th>Typical Systems Engineering Activity</th>
<th>Left End of Slider</th>
<th>Left Intermediate Interval</th>
<th>Center Intermediate Interval</th>
<th>Right Intermediate Interval</th>
<th>Right End of Slider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Define the System Problem</td>
<td>Establish System Requirements</td>
<td>Adapt to Changing Requirements; Re-Scope</td>
<td>Revise and Restate Objectives</td>
<td>Try to Predict Future Enterprise Needs</td>
<td>Discover Needed Mission Capabilities</td>
</tr>
<tr>
<td>Analyze Alternatives</td>
<td>Conduct Systems Tradeoffs</td>
<td>Model/Simulate System Functionalities</td>
<td>Perform Systematic Cost-Benefit Analyses</td>
<td>Include Social and Psychological Factors</td>
<td>Emphasize Enterprise Aspects</td>
</tr>
<tr>
<td>Utilize a Guiding Architecture</td>
<td>Apply an Existing Framework</td>
<td>Develop Architectural Perspectives (Views)</td>
<td>Really Define (Not Just Views of) Architecture</td>
<td>Adapt Architecture to Accommodate Change</td>
<td>Embrace an Evolutionary Architecture</td>
</tr>
<tr>
<td>Pursue Solutions</td>
<td>Advocate One System Approach</td>
<td>Consider Alternative Solution Approaches</td>
<td>Investigate Departures from Planned Track</td>
<td>Iterate and Shape Solution Space</td>
<td>Keep Options Open While Evolving Answer</td>
</tr>
<tr>
<td>Manage Contingencies</td>
<td>Emphasize and Manage System Risks and Watch Opportunities</td>
<td>Mitigate System Risks and Watch Opportunities</td>
<td>Sort, Balance and Manage All Uncertainties</td>
<td>Pursue Enterprise Opportunities</td>
<td>Prepare for Unknown Unknowns</td>
</tr>
<tr>
<td>Develop Implementations</td>
<td>Hatch System Improvements Off-Line</td>
<td>Prepare Enhancements for Fielding</td>
<td>Experiment in Operational Exercises</td>
<td>Develop in Realistic Environments</td>
<td>Innovate With Users Safely</td>
</tr>
<tr>
<td>Integrate Operational Capabilities</td>
<td>Test and Incorporate Functionalities</td>
<td>Work Towards Better Interoperability</td>
<td>Advance Horizontal Integration As Feasible</td>
<td>Advocate for Needed Policy Changes</td>
<td>Consolidate Mission Successes</td>
</tr>
<tr>
<td>Learn by Evaluating Effectiveness</td>
<td>Analyze and Fix Operational Problems</td>
<td>Propose Operational Effectiveness Measures</td>
<td>Collect Value Metrics and Learn Lessons</td>
<td>Adjust Enterprise Approach</td>
<td>Promulgate Enterprise Learning</td>
</tr>
</tbody>
</table>

Convenient Labels (Only; interpret them): Engineering (TSE) Complex Systems Engineering (CSE)
Complex Systems Engineering Principles

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.
Complex Systems Engineering Principles (Concluded)

8. Formulate heuristics (practical rules of thumb) and educate emotions [7] to assist decision makers.

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.


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.
Requirements entailed interconnecting

- Tens of Mb/s digital trunks from 40 metropolitan centers
- Several-Mb/s user-user channels.

Assumptions

- Near-geostationary satellite
- Tens of simultaneous beam-hopping (or scanning) and high-gain satellite antennas
- Reuse of 2.5 GHz wide ($K_a$-band) allocations
- On-board microwave switch with tens of input/output ports
- All-digital on-board processor for demodulation/decoding, baseband switching, and recoding/remodulation

Principles 1 and 6 applied

- LeRC management were suitably humble
- They created atmosphere that facilitated inputs and fresh ideas

Principle 5 also was huge

- Political, operational, and economic objectives were as important as $K_a$-band technology
  - Retention of lead in satellite communications
  - Operational demonstration of $K_a$-band
  - Affordable capabilities
Initial On-Board Processing Satellite Architecture

Wideband Trunking Service

RXs = receivers
TXs = transmitters

Drop

Microwave Switch

Add

RXs

Demodulator
Decoder

Control

Coder
Modulator

TXs

Demultiplexer

Digital
Processor

Baseband
Switch

Multiplexer

Direct-to-User Service

(uplink) fixed spot beam array

(downlink) fixed or scanning spot beam

beam pointing control

Digital Control

Command
Subsystem

Telemetry
Subsystem

See Notes Page
System alternatives were considered following Principle 2 instead of reductionism/constructionism.

All alternatives were backed by theories:
1. Shannon’s channel capacity ($R_o$)
2. Viterbi’s maximum-likelihood decoding
3. Bandwidth-Power efficient modulation tradeoffs
4. Bandwidth efficient modulation for low cross-talk satellite uplinks
5. Demand assignment multiple access
6. Multiple beam optimizations
7. Large (e.g., $100 \times 100$) IF (2-4 GHz frequency) switches

Principle 3 was applied to ensure that both wideband trunking and direct-to-user service were aptly accomplished.

Areas 3, 4, 6, and 7 were deemed most important.
Initial on-board processing definition **SoS I** consisted of:
- TDMA uplink, on-board IF switch, and TDM downlink for the trunking channels
- Uplink FDMA, on-board baseband processing, and downlink TDM for the direct-to-user Customer Premises Service (CPS)

There were contractor studies/proposals and common-carrier sentiment for TDMA/TDM:
- NASA had traffic model of many postulated users/cities with very high data rates
- Prevailing opinion: TDMA could provide these services more efficiently than FDMA
- But this implied more expensive earth terminals
- Only General Electric’s Space Systems Division had advocated an all FDM concept

**LeRC** asked **MITRE** to investigate FDMA/FDM system:
- Opportunity for innovation with relative risks, i.e., Principle 7 was exercised
- Visited GE but examined own alternatives: FDMA uplink, no on-board baseband processing, and FDM downlink
- Exemplar FDMA/FDM version called **SoS II**
LeRC contemplated MITRE’s study results and brought on private industry; 1984 contract was awarded to

- RCA Astro, East Windsor, NJ
  - system integration and spacecraft bus
- 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 subcontracted with

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

ACTS launched in 1993 called SoS III
Ensuing Benefits

- LeRC exemplified Principle 9 (Trust), making collegial friends with all contractors. Kept us informed about program status, how their thinking was evolving, and inspired a continual focus on good planning.

- ACTS was used as “Switch-board in the Sky” testbed for more than 50 special ground terminals and 100 experimenters, in fields of, e.g.,
  - Computer networking
  - Telemedicine
  - Petroleum (industry)
  - Education
  - Defense
  - Business
  - Emergency response
  - Mobile communications
  - Astronomy

- Experiments continued until 2000
- From 2001 to 2004 ACTS was used for educational research
Exemplar Concept of SoS I

Solar Cell Arrays

Fixed Multi-beam Antenna with Satellite Switched TDMA

Scanning Beam Antenna with Baseband Processing and Switching

Customer Premises Terminals

Trunking Terminal

Rain Diversity Trunking Terminal
Satellite-Routed FDMA Concept of SoS II

Uplink

 Filters

- Band 1
- Band 2
- Band 3
- Band 4

Downlink

Beam a

Beam b

Beam A

Beam B

Multi-Channel Earth Terminals

User i Modem

Synthesizer

User j Modem

User k Modem

User l Modem

Synthesizer

PA

PA

PA

PA

Band 1

Band 2

Band 3

Band 4

to Beam a: \( f_1 \neq f_3 \)
to Beam b: \( f_7 \neq f_6 \)
to Beam a: \( f_1 \neq f_3 \)
to Beam b: \( f_7 \neq f_6 \)

Band 1

Band 2

Band 3

Band 4

from Beam A:

Band 1

Band 2

f

to Beam a: \( f_3 \)
to Beam b: \( f_6 \)

from Beam B:

Band 4

Band 3

f
ACTS of SoS III

Dual sub-reflectors

C-band omni-directional antenna

Beam-forming networks

20 GHz Tx antenna

Solar array

Ka-band command, ranging, and telemetry antennas

30 GHz Rx antenna

Spacecraft body

Steerable antenna

Solar array

Spacecraft dimensions

15.2 ft
29.9 ft
47.1 ft

ACTS of SoS III

See Notes Page
Other Aspects

- **Budget**
  - ACTS budget was capped at $499M by Congress.
  - MITRE portion lasted only 2 years at 6 staff years per year

- **Mission/Purpose/Goal/Objective**
  1) Realize information “super highway” *in space*
  2) Make space technological breakthroughs in the K/Ka-band
  3) Create opportunities for commercial U.S. companies
  4) Protect and further ensure U.S. lead in satellite communications

- **Principles/Characteristics**
  - LeRC “led the charge” embracing and applying many SoSE principles in employing the overall precept of openness (embodied in Principles 1-3, 5-7, 9-10, 12, and as noted below, 11 and 13).
ACTS Relationships and Responsibilities

- Program Management
- Advancement of Innovative Satellite Communications Technologies
- Ground Terminal Provisions
- Spacecraft Launching
- System Operations

- Technical Advice
- Concepts Introduction
- Alternatives Analyses & Evaluations
- In-Depth System Studies
- Technical Oversight

- Computer networking
- Telemedicine
- Petroleum (industry)
- Education, Defense, Business
- Emergency response
- Mobile communications
- Astronomy

- Contractual Engagements
- System Proposals
- Technical Trade-offs & Advice
- Final Designs & Implementations

See Notes Page
External Factors and Constraints

- Limitation maturity and high cost of $K_a$-band technology were prime motivations for ACTS
- Competition with EHF Military Strategic and Tactical Relay (MILSTAR) satellite program

Constituents (new/legacy, scope)

- ACTS and MILSTAR cross-fertilized because Lockheed Martin was prime contractor on both programs
- Each benefited through complex systems Principle 11 (Self-Organization) of continual collaboration and competition
# SoS Engineering Analysis

## SoS I Characteristics

<table>
<thead>
<tr>
<th>Item</th>
<th>Trunking Channel</th>
<th>Customer Premises Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Satellite Beams</td>
<td>40 fixed</td>
<td>2 scanning</td>
</tr>
<tr>
<td>Modulation</td>
<td>DQPSK* (up/down)</td>
<td>DQPSK/CQPSK**</td>
</tr>
<tr>
<td>Access (uplink/downlink)</td>
<td>TDMA/TDM</td>
<td>FDMA/TDM</td>
</tr>
<tr>
<td>Bandwidth/Beam</td>
<td>2400 MHz</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Data Rate/Beam</td>
<td>3300 Mb/s</td>
<td>150 Mb/s</td>
</tr>
<tr>
<td>Sat. Ant. Dia. (30/20 GHz)</td>
<td>3.4/5.1 m</td>
<td>1.5/2.3 m</td>
</tr>
<tr>
<td>Terminal Ant. Diameter</td>
<td>7.3 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Terminal RF*** power</td>
<td>30 W</td>
<td>6 W</td>
</tr>
<tr>
<td>No. Terminals</td>
<td>80</td>
<td>5000</td>
</tr>
<tr>
<td>Total Terminal Cost</td>
<td>$87 M</td>
<td>$505 M</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Weight</td>
<td>5200 lb</td>
</tr>
<tr>
<td>Satellite Power</td>
<td>2630 W</td>
</tr>
<tr>
<td>Satellite Cost</td>
<td>$89 M</td>
</tr>
<tr>
<td>Non-Recurring Engineering Cost</td>
<td>$300 M</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$981 M</td>
</tr>
</tbody>
</table>

* Differential Quadrature Phase Shift Keying
** Compatible differential offset QPSK
*** Radio Frequency
Beam Plans for Six-Region SoS II

USA FROM 90 DEGREES LONGITUDE

CPS BAND

BEAM:

TRUNKING BAND

V = VERTICAL POLARIZATION
H = HORIZONTAL POLARIZATION
■ = NO TRUNKING BAND ALLOCATED

850 MHz
400 MHz
1.7 GHz
2.5 GHz
800 MHz

See Notes Page
SoS Engineering Analysis (Continued)

- **Activities/Problems/Conflicts (within MITRE)**
  - Inter-personnel issues were resolved with only positive impacts on the technical work
  - Inter-team rivalries in solving SoS I and SoS II problems benefited from this competition and collaboration

- **Timeframe/Sequence of Events (NASA)**
  - Refining Space Shuttle design and launching experimental Shuttle flights
  - Rethinking their “roles and missions” alternatives
  - Furthering advanced space communications technology and applications

- **Methods and Tools Used**
  - “SoS” did not exist prior to launch; Wikipedia’s first reference to SoS is dated 1996
  - Several tools and models were used during study, including NASA’s data traffic model
  - MITRE Interactive Communications Analysis Program (MICAP) was used to analyze satellite system communications alternatives, including satellite and terminal costs.
  - Propagation perturbation effects on EHF communications links utilizing rain attenuation models were exercised. MILSATCOM Program Office cost models were also employed.
Lessons Learned

MITRE study recommendations were too ambitious considering relatively modest capability ultimately implemented. For example, ACTS included

- $3 \times 3$ IF switch, whereas MITRE had investigated $100 \times 100$ switch
- 5 scanning beams whereas MITRE studies had assumed up to 40 fixed beams and 2-8 scanning beams

Sometimes simpler but less capable solutions sit better with customer(s), especially considering ultimate system cost as an independent variable!

Best Practices

Thorough investigations of many SoS alternatives and technical issues and close attention to detail characterized the MITRE studies

LeRC

- Was faithful to potential users in
  - Generating traffic model
  - Providing experimentation terminals
- Listened to industry and utilized their technical inputs

Steps and Conditions for Replicating the SoS Elsewhere

LeRC methodology in investigating and developing new technology demonstrations that significantly advance state-of-the-practice is worth pursuing
Conclusion

- ACTS was highly successful
  - Study of system alternatives benefited final design
  - Industrial contractors created K-Band technology satellite
  - Experiments for users advanced the state-of-the-art
- Many CSE principles were in play but
  - Principles 4 and 8 were not in evidence
    - Soft sciences have become much more relevant
    - Decision making is dependent upon our sub-conscious and emotions
Questions for (Classroom) 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?
References

References (Concluded)


Backup Charts
CSE Principles

1. Bring Humility
2. Follow Holism
3. Achieve Balance
4. Utilize Trans-Disciplines
5. Embrace POET*  *Political, Operational, Economic, and Technical
6. Nurture Discussions
7. Pursue Opportunities
8. Formulate Heuristics
9. Foster Trust
10. Create Interactive Environment
11. Stimulate Self-Organization
12. Seek Simple Elements
13. Enforce Layered Architecture

Abbreviated Principle Definitions

1. Bring Humility

This has been attacked as unprofessional.

What do you think?

Simple fixes often don’t work in complex situations.

One must watch carefully and be prepared to try something else.

But one is rarely sure just how long to wait to act (again).
2. Follow Holism

One cannot use reductionism
Complex system and its environment will have moved
Fundamental problem with government system acquisitions

3. Achieve Balance

Optimizing sub-systems detracts from efficacy of whole
Try to balance various sub-system thrusts

4. Utilize Trans-Disciplines

People are part of system.
“Trans-disciplines” like philosophy, psychology, sociology, organizational change theory, economics, and politics apply

(White 2010)
5. Embrace POET
   Deal with all four aspects
   Understand stakeholders’ values

6. Nurture Discussions
   Every person sees differently
   No one grasps whole truth
   Leverage group’s cognitive diversity
   Understand how words are used

7. Pursue Opportunities
   Too much emphasis on identifying/mitigating risks
   Principal risk is not pursuing opportunities
   Strike balance

(White 2010)
8. Formulate Heuristics

Devise rules-of-thumb to help decision-makers
Time delays are tantamount

9. Foster Trust

Establishing trust is difficult and can be lost immediately
Try sharing some information
If echoed, share more and more

(White 2010)
10. Create Interactive Environment
   Establish/maintain interactions and their reward structures
   Act and be responsive
   Don’t fight systems that cannot be influenced
   Solicit inputs from external observers

11. Stimulate Self-Organization
   This is natural state for living elements

(White 2010)
12. Seek Simple Elements

SE solutions are often too big and/or complicated
Design down-scale and assemble smaller adaptable units

13. Enforce Layered Architecture

Apply layering principles
Each layer can be adapted to different conditions
Keep interface(s) between layers unchanged

(White 2010)