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

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Outline of Talk

- Introduction
- Profilers
- Principles
- The Problem
- System Designs
- The Results

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NASA's Lewis Research Center (LeRC) Advanced Communications Technology Satellite (ACTS)

- 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

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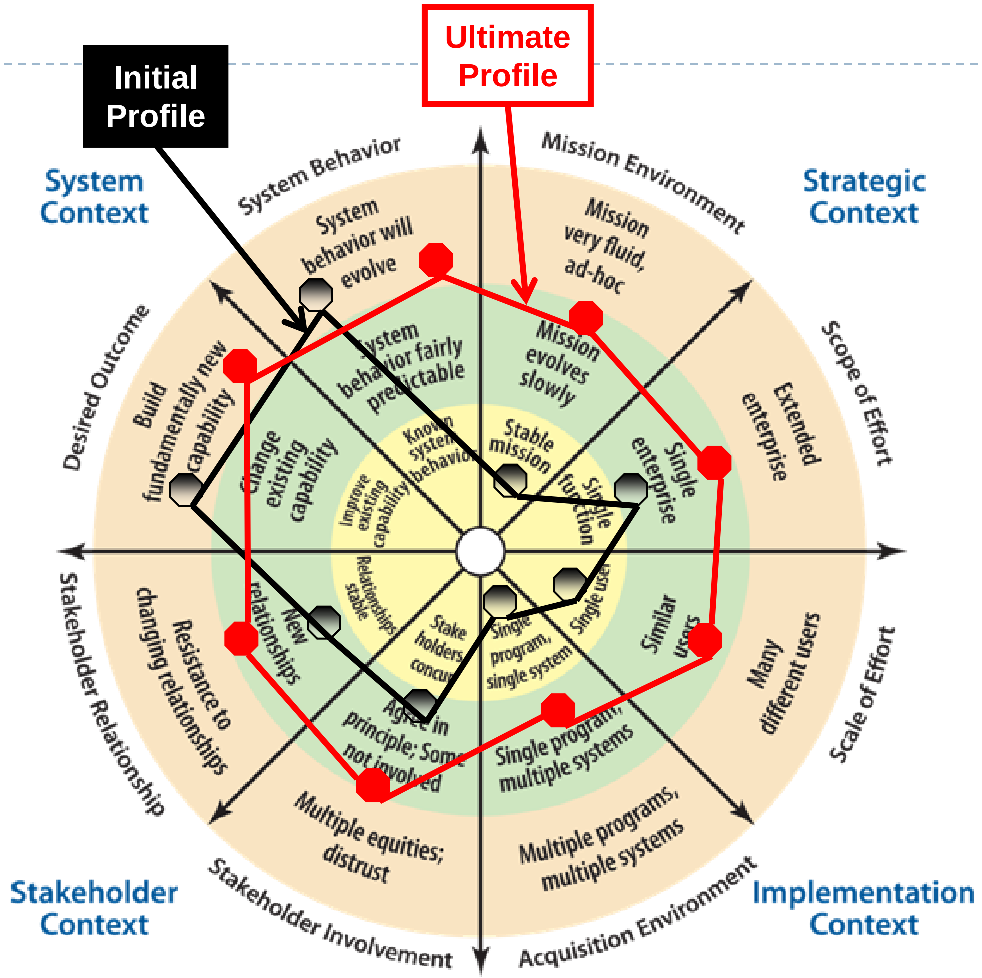

- Traditional program domain
  - *Well-bounded problem*
  - *Predictable behavior*
  - *Stable environment*
- Transitional domain
  - *Systems engineering across boundaries*
  - *Influence vs. authority*
- Messy frontier
  - *Political engineering (power, control…)*
  - *High risk, potentially high reward*
  - *Foster cooperative behavior*

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Systems Engineering Activities (SEA) Profiler

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Version 4 – 4 Jan 09

Initial Profile | **Ultimate Profile**

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

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

Aggregate Assessment of Above Slider Positions

Complex Systems Engineering Principles

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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.

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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.

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.

Context

- 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 1and 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

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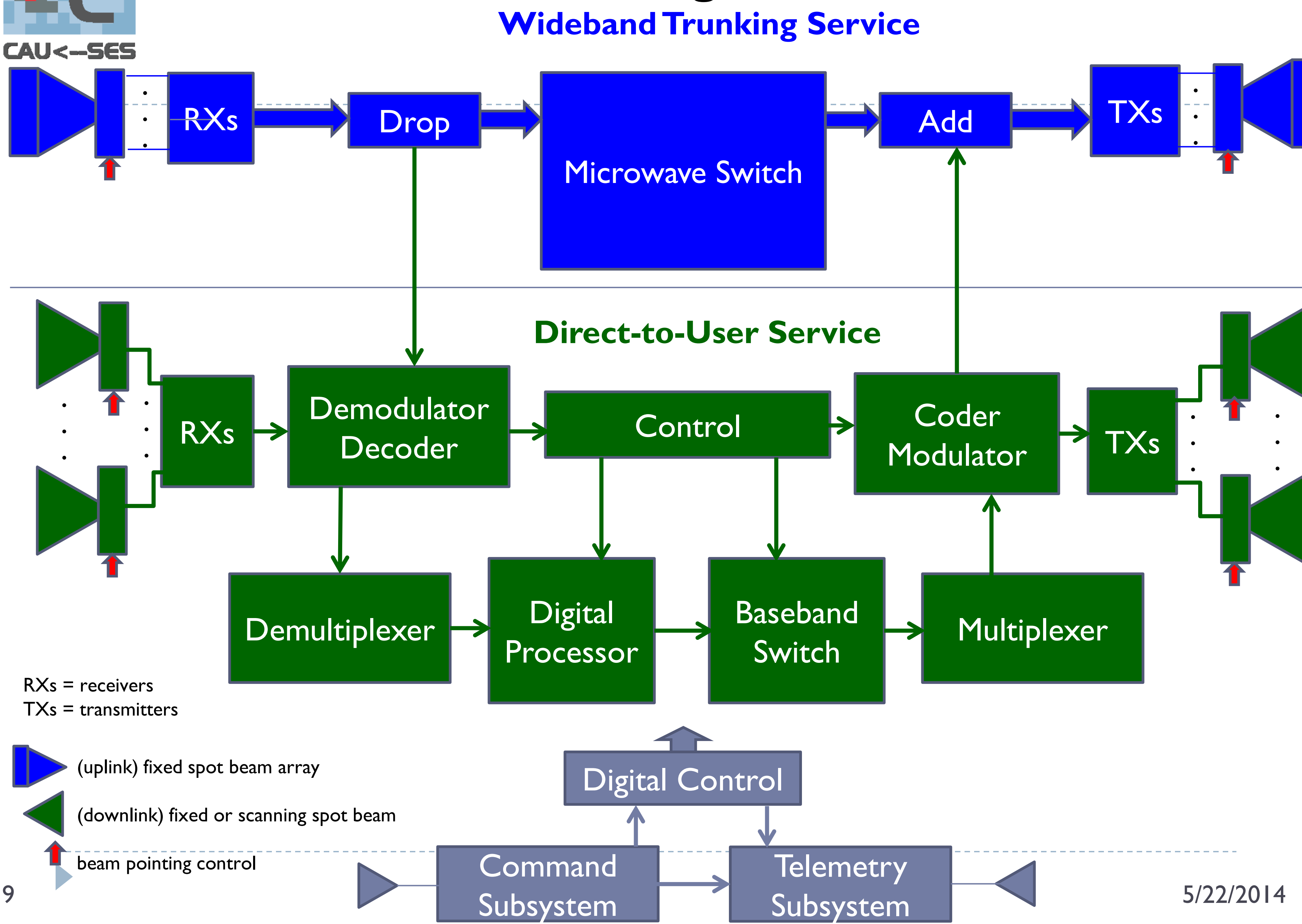
Initial On-Board Processing Satellite Architecture



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Relevant Theories—Prior Research

- 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 × 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

SoS Descriptions—History/Development

- 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, <u>no</u> on-board <u>baseband</u> processing, and FDM downlink
  - Exemplar FDMA/FDM version called **SoS II**

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Other Contractor Efforts

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- 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**

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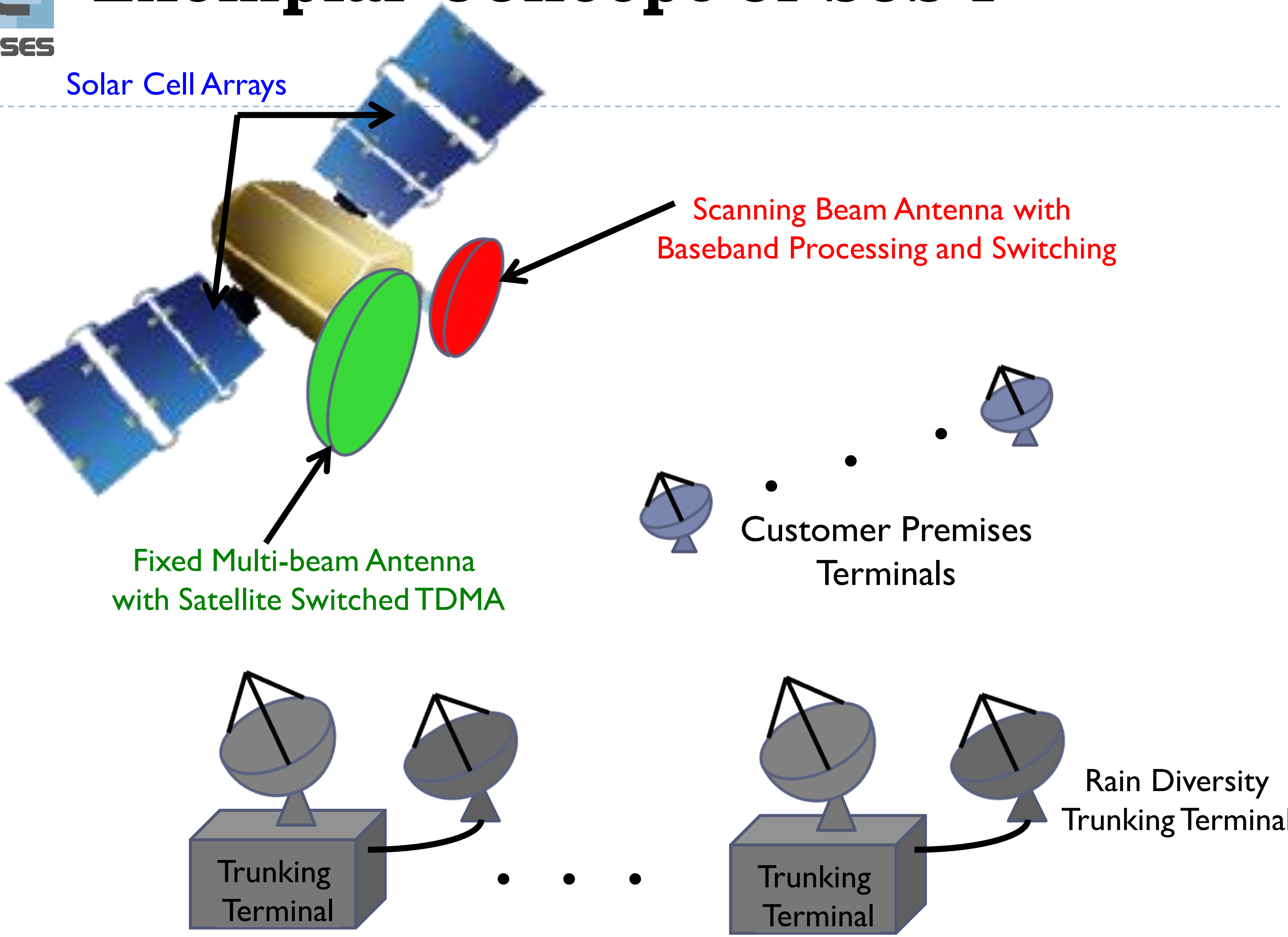
Ensuing Benefits

- 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



Satellite-Routed FDMA Concept of SoS II

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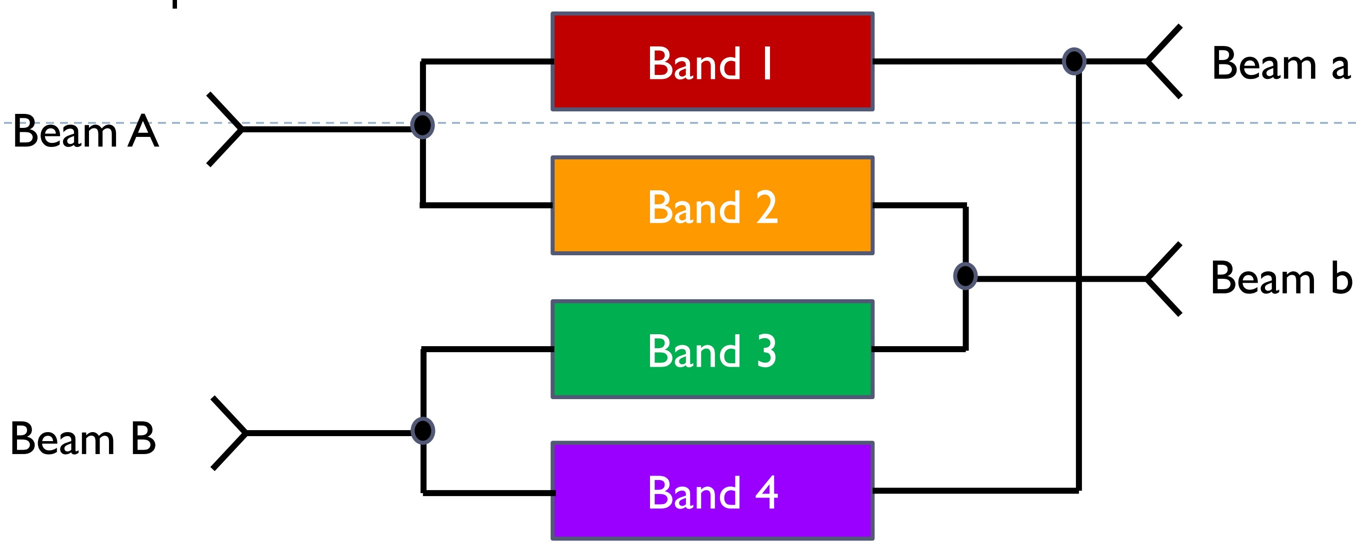
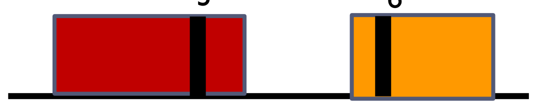
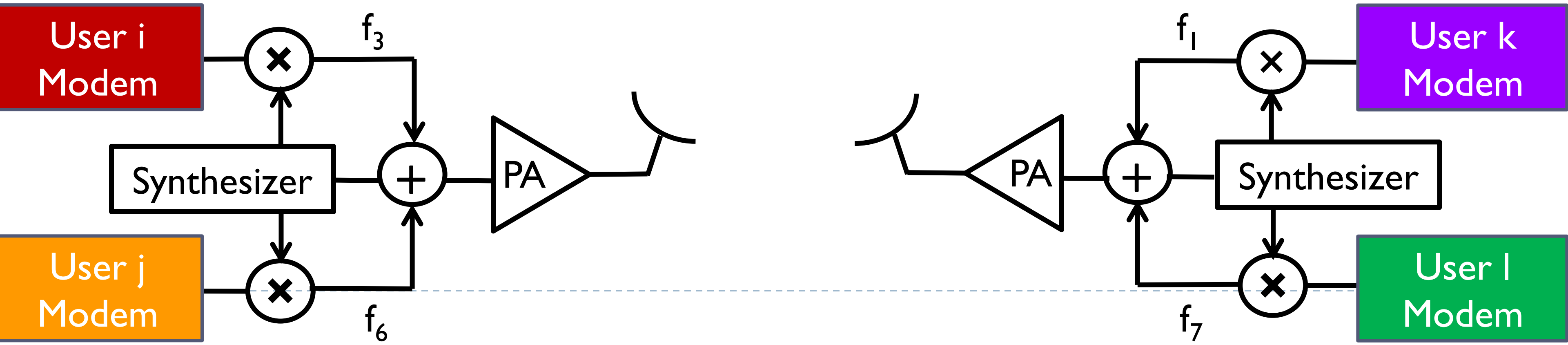
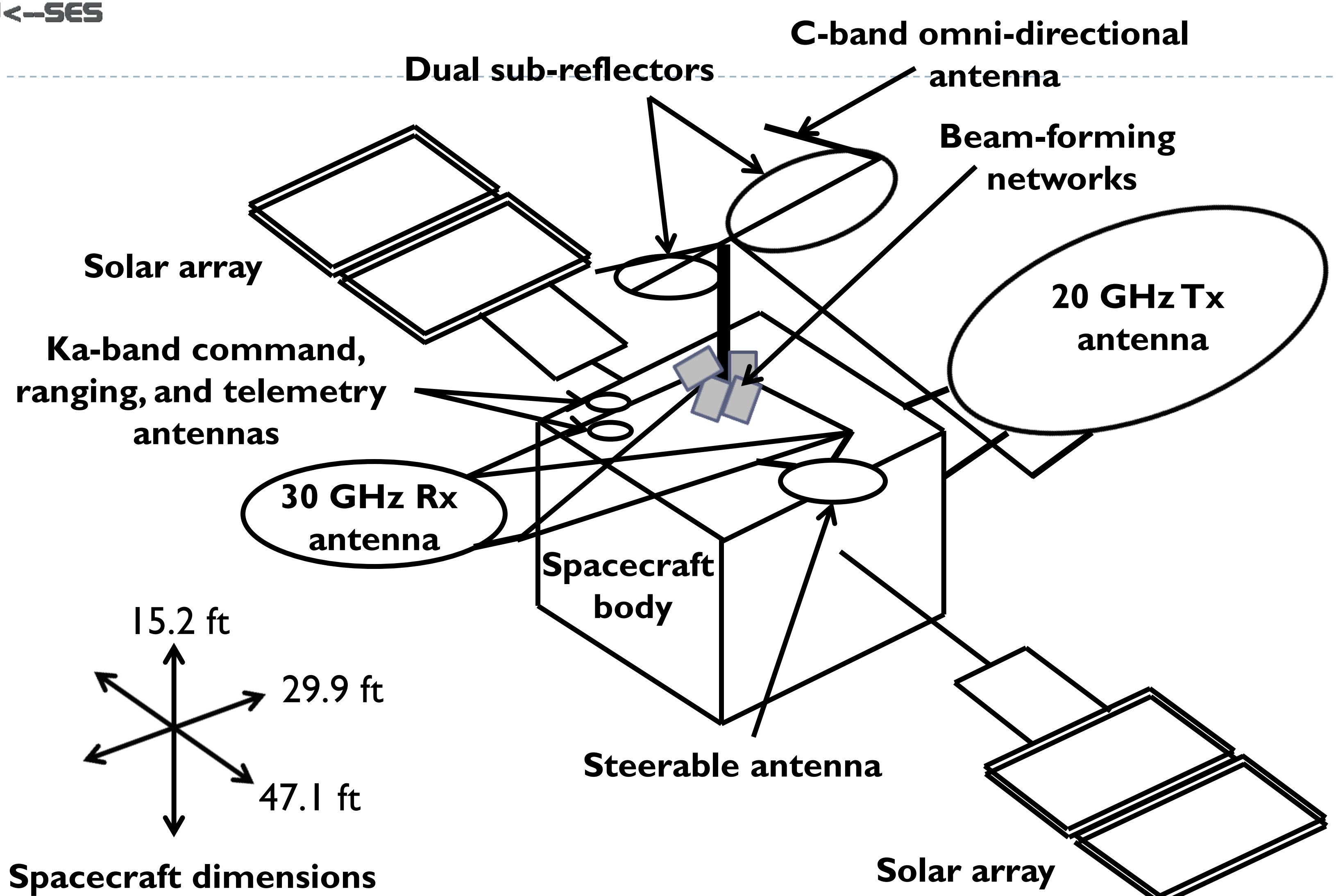






Multi-Channel Earth Terminals

ACTS of SoS III



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/K_a-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).

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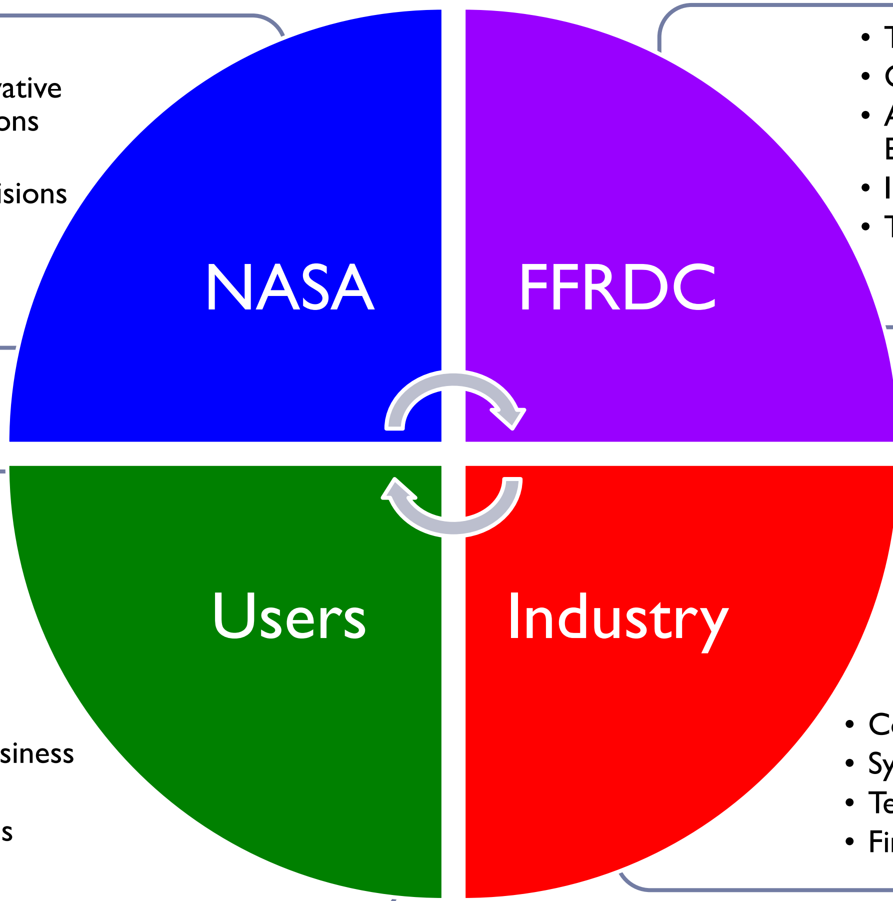
ACTS Relationships and Responsibilities

- 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

Other Aspects (Concluded)

- **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

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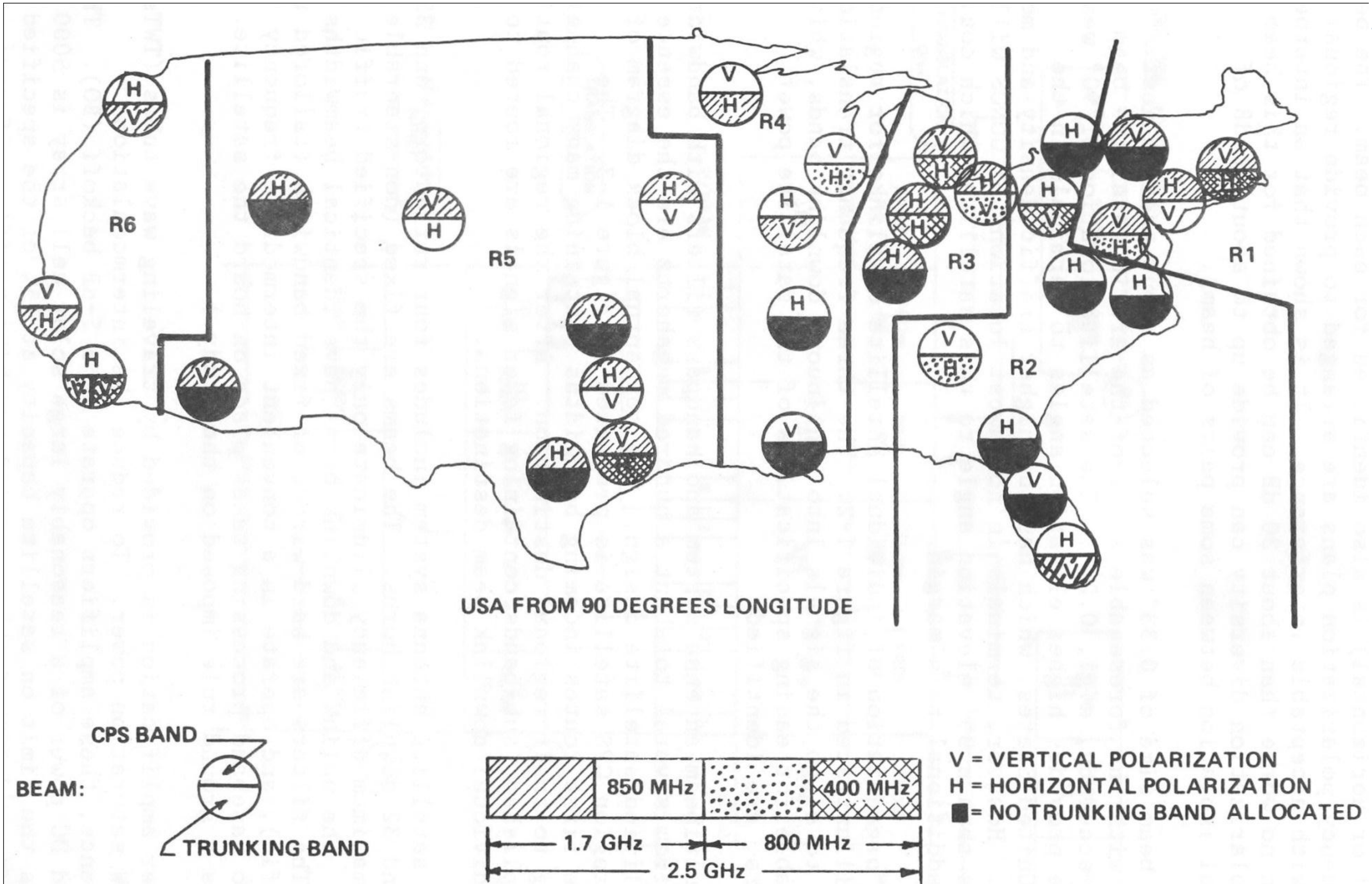
Item	Trunking Channel	Customer Premises Channel
No. Satellite Beams	40 fixed	2 scanning
Modulation	DQPSK* (up/down)	DQPSK/CQPSK**
Access (uplink/downlink)	TDMA/TDM	FDMA/TDM
Bandwidth/Beam	2400 MHz	100 MHz
Data Rate/Beam	3300 Mb/s	150 Mb/s
Sat. Ant. Dia. (30/20 GHz)	3.4/5.1 m	1.5/2.3 m
Terminal Ant. Diameter	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

Beam Plans for Six-Region SoS II



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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.

SoS Engineering Analysis (Concluded)

- **Lessons Learned**
  - MITRE study recommendations were too ambitious considering relatively modest capability ultimately implemented. For example, ACTS included
    - 3×3 IF switch, whereas MITRE had investigated 100×100 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

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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

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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?

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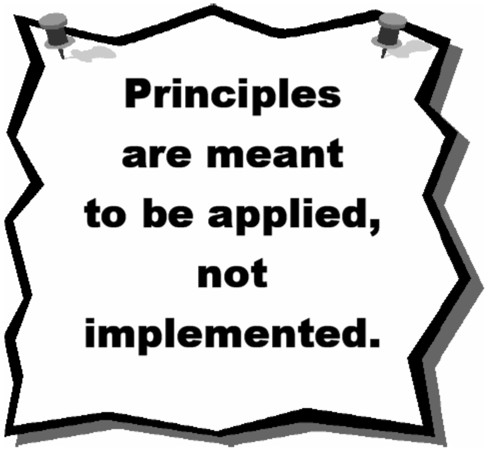
Backup Charts

CSE Principles

1. Bring Humility
2. Follow Holism
3. Achieve Balance
4. Utilize Trans-Disciplines
5. Embrace POET*
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

* Political, Operational, Economic, and Technical



(White 2010) B. E. White, "A 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; won best paper award.

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).

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Abbreviated Principle Definitions (Continued)

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)

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Abbreviated Principle Definitions (Continued)

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 <u>not</u> pursuing opportunities
   - Strike balance

(White 2010)

Abbreviated Principle Definitions (Continued)

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)

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Abbreviated Principle Definitions (Continued)

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)

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Abbreviated Principle Definitions (Concluded)

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)