Space Solar Power (SSP) Concept and Technology Maturation (SCTM) Program

Systems Integration, Analysis and Modeling Status and Plans

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SSP Systems Studies and Analysis

DESCRIPTION

Systems Studies and Analysis includes developing and using detailed SSP system and subsystem models to identify promising concepts, orbits & metrics to focus SSP R&D. Modeling is used to highlight interactions between subsystems and technologies that must be understood for system trades and to track the viability of concepts and design approaches as technologies mature.

APPROACH

- Advanced concept definition studies
- Development of evolutionary scenarios
- Analysis of systems and architecture concepts
- High-level modeling of systems, architectures and operations
- Commercial terrestrial and space market analysis and outreach

SIWG PARTICIPANTS

- NASA Glenn Research Center (Lead)
- Other NASA centers: MSFC, JPL, JSC, GRC, GSFC
- Non-NASA Organizations: SAIC, TBD
- Universities: TBD

SERT SIWG REVIEW

System Modeling and Analysis Issues From SERT

- **Residual Issues from SERT**
  - Laser concepts not fully defined and modeled
  - Updates needed for many existing subsystem worksheets
  - Robotics, space assembly and operations not modeled adequately
  - New ground segment model needed to accommodate laser systems
  - Better model needed to reflect benefits of high production manufacturing
  - Improvements in cost estimation (particularly non-recurring) needed
  - Difficult to introduce new system concepts and configurations in model
- **Applicability:**
  - All concepts
- **Priority:** High
- **Recommended Resolution: (Done =** √, Started = ◊, Pending = –)
  - √ Review and model laser system concepts introduced in SERT
  - ◊ Update Structures, Attitude Control, Thermal, TCM/CDH worksheets
  - – Develop new worksheets for robotics, operations, ground segment
  - – Incorporate results of manufacturing and cost estimation study efforts
  - √ Develop new modeling architecture separating technologies from concepts
- **Lead Working Group:** SIWG
- **Key Participating WG's:** All

Recap of Candidate SSP Concepts Identified in SERT

RF CONCEPTS

- **Sun Tower Derivatives (Gravity Gradient GEO Satellites)**
- **Abacus Reflector**
- **Integrated Symmetrical Concentrator**
- Halo Orbit Concept
- Sandwich Concept
- Others

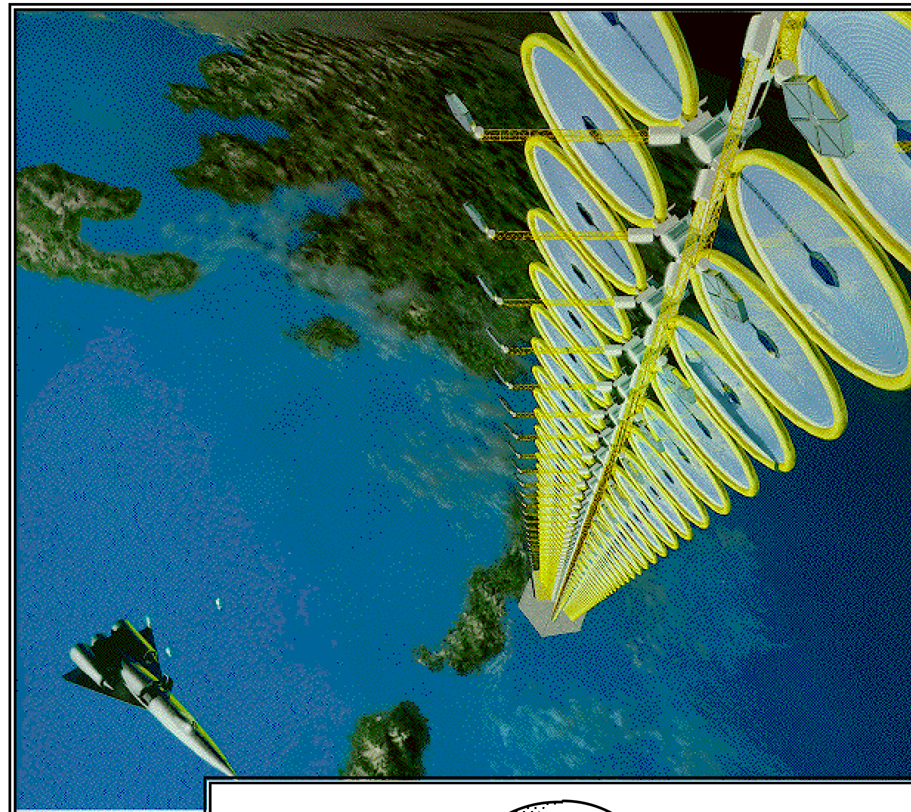
LASER CONCEPTS

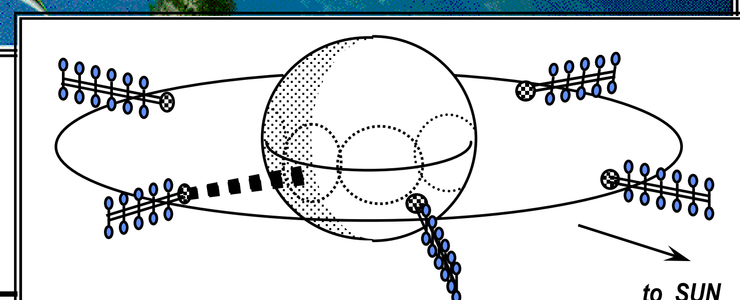
- **Laser Diode/Fiber Sun Tower - Halo Orbit (Aerospace)**
- **Laser Diode/Fiber Sun Tower - Gravity Gradient (Boeing)**
- Laser Diode/Mirrored Optics Concept - Halo Orbit (UAH)

Bold = Concepts either modeled or undergoing modeling by SIWG

SCTM Systems Integration, Analysis and Modeling
Original Sun Tower SPS Concept

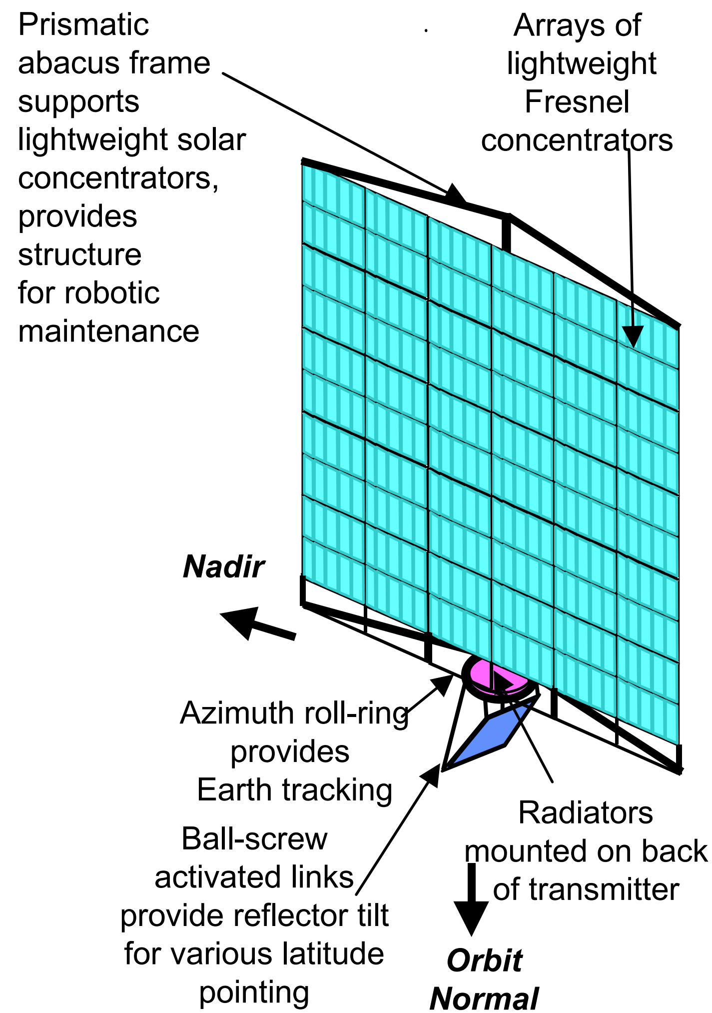
- **System Concept**
  - Modular systems; self-assembling at high LEO
  - Gravity-gradient / GN&C stabilized
  - Aggressive technology for solar arrays, integrated propulsion, others
  - RF phased array for Wireless Power Transmissio
- **Architecture**
  - 12,000 KM equatorial orbit
  - ± 30 degrees Latitude Coverage
  - Power services of ~ 400 MW (example)
  - Requires moderate terrestrial energy storage (level varies depending on platform configuration and specific orbit)
  - ~12 SPS yields power to 12 sites, etc.
  - Power for Emerging Markets: South & Central America, Africa, Asia, India...
- **Transportation**
  - Deployment using Commercial Launch Services (RLV-class @ $400/kg)





Abacus Reflector SPS Concept

- Solar collectors always face Sun with very little, if any, shadowing
- Solar concentrator uses shifting lens to accommodate seasonal beta-tracking, eliminates rotational joints between cells and abacus frame
- Reflector design eliminates massive rotary joint and slip rings of 1979 Reference concept
- Fixed orbital orientation allows continuous anti-Sun viewing for radiators
- Abacus structural frame provides runs for PMAD cabling and permits "plug and play" solar array approach for assembly and maintenance
- Triangular truss structure provides reasonable aspect ratio for abacus
- Activated links provide reflector tilt for target latitude accessability
- Reduced rotational mass since rotating reflector structure can be made much lighter than large planar transmitter array



RF Reflector/Abacus Concept

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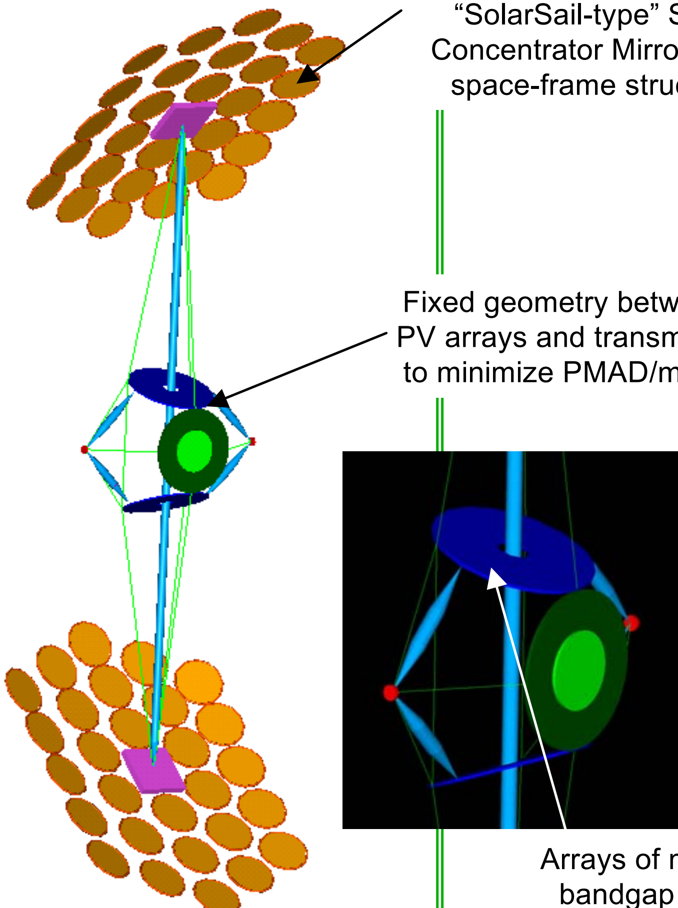
Integrated Symmetrical Concentrator SPS Concept



- Solar collectors always face Sun with very little, if any, shadowing
- Sunlight Reflector design eliminates massive rotary joint and slip rings of 1979 Reference concept
- Fixed orientation allows continuous anti-transmitter viewing for PV heat rejection
- Mirror approaches minimizes on-platform PMAD mass – a *dramatic* improvement
- Reduced rotational mass since rotating reflectors and structure can be made much lighter than large PV arrays

Integrated Symmetrical Concentrator Concept

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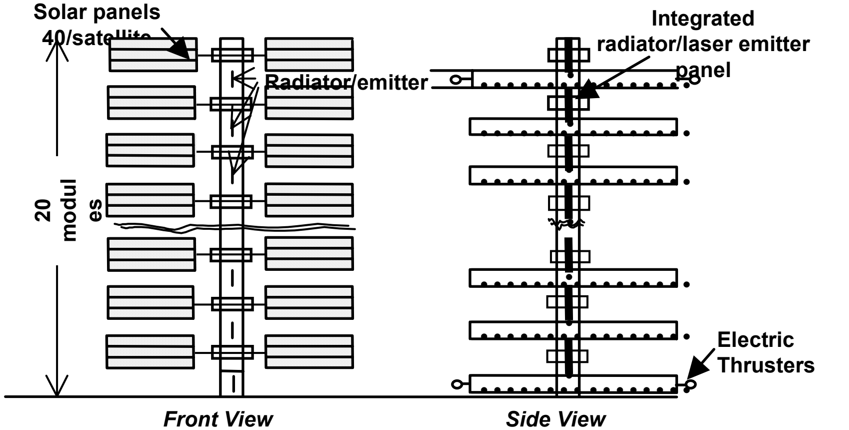
Laser SPS Concepts

Aerospace Corp's Laser WPT SPS in Halo Constellation

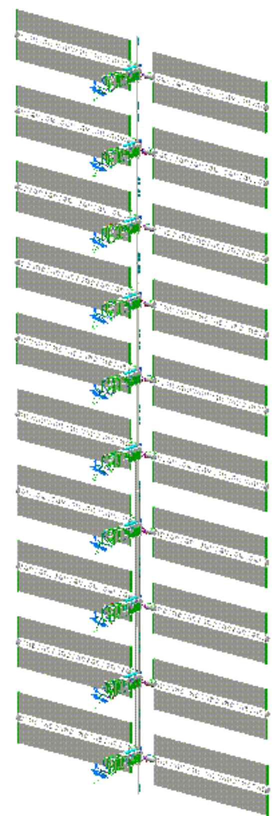


(at point of orbit when radiators are perpendicular to array)

THE AEROSPACE CORPORATION

Boeing's "Skylight"
A Megawatt-Class SSP

- **Gravity-gradient Sun Tower-like configuration**
- **10 pairs of rotating arrays, each consisting of 2 ISS-size solar panels**
  - S/C overall length of 170m
  - 2.7 MW of array power provides ~1kW beam
- **Distributed laser WPT system**
  - Each solar collector pair on space segment has its own optics at center (shown) or on edge
  - Wavelengths are available to provide good atmospheric transmission and a good match to several PV receiver cells



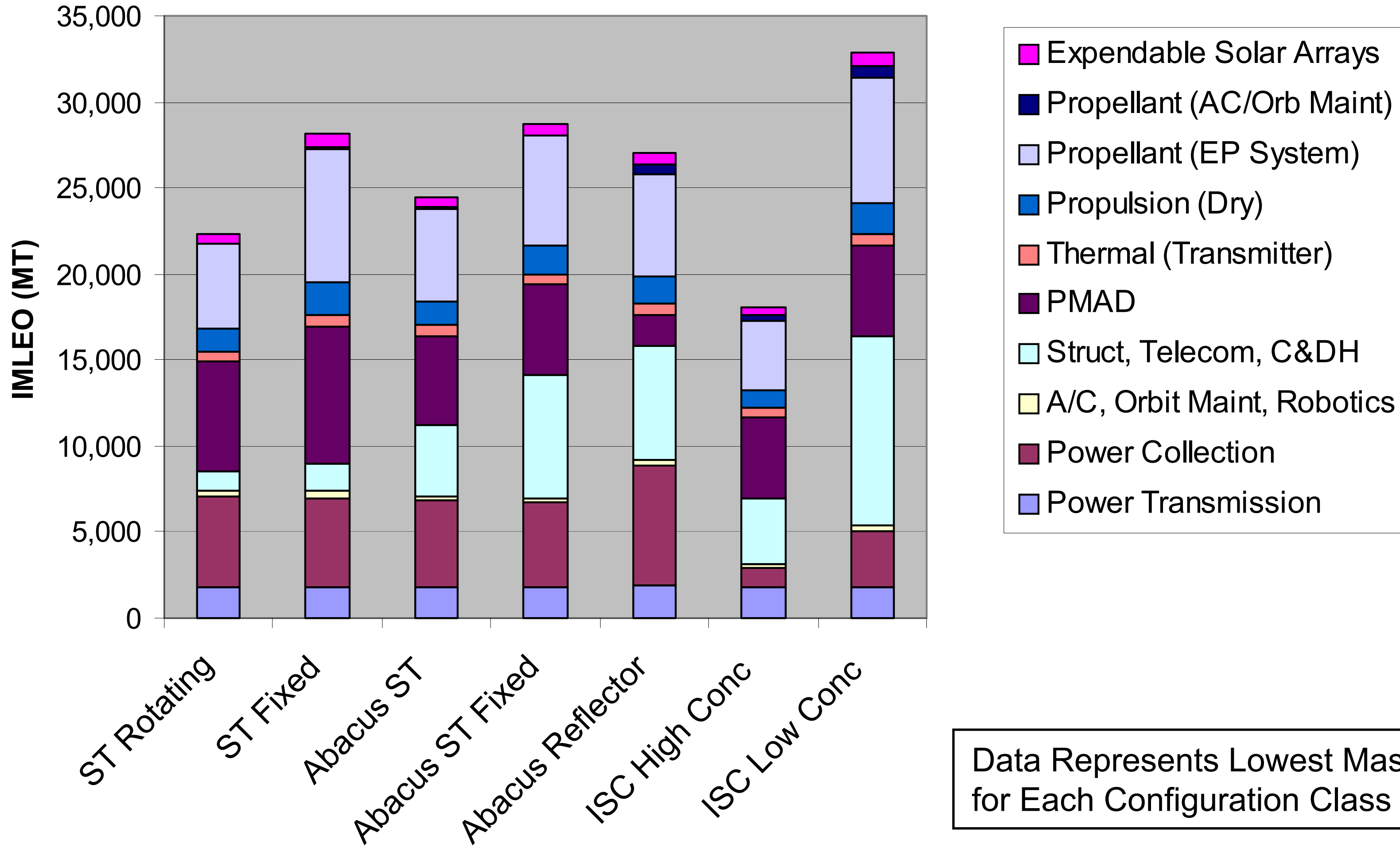
~53MT without energy storage

BOEING

SERT RESULTS

SCTM Systems Integration, Analysis and Modeling

SERT Results: Mass Comparison of Candidate Configurations

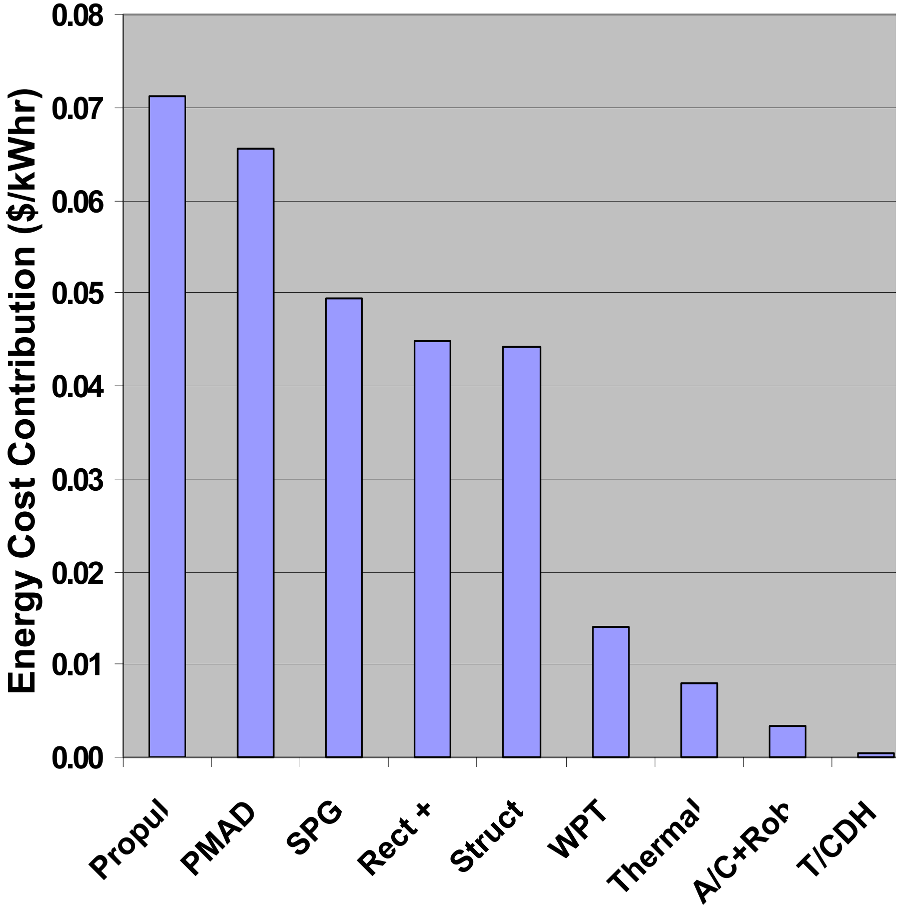


Data Represents Lowest Mass
for Each Configuration Class

SERT Results: Subsystem Contributions to Energy Cost (1 of 2)

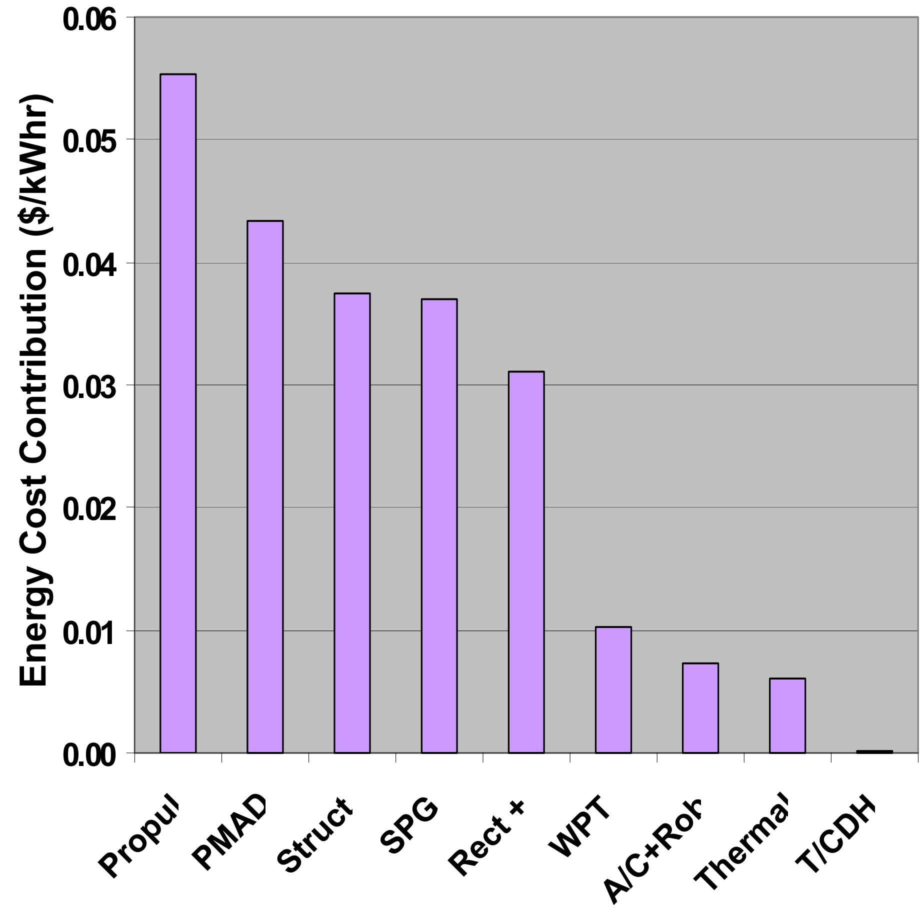
Abacus Sun Tower Rotating Arrays (MTA)

Estimated Cost of Electricity ~ 30.1¢ per kW-hr



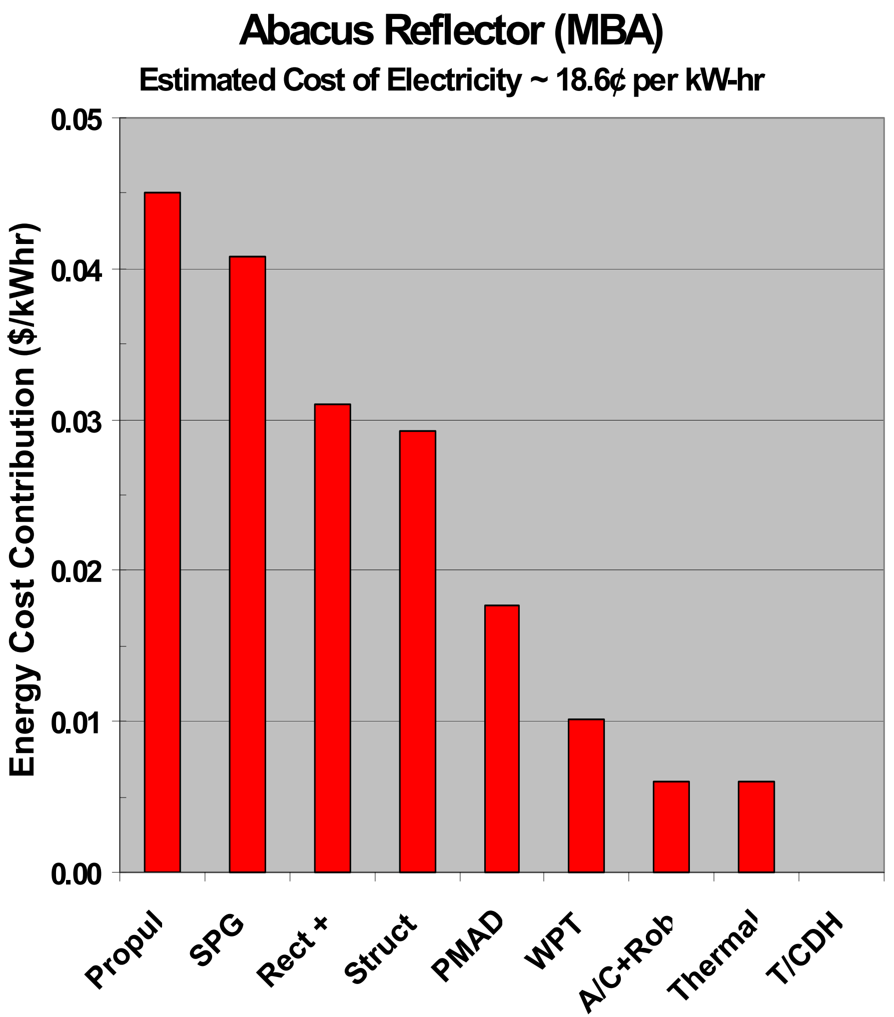
Abacus Reflector (MTA)

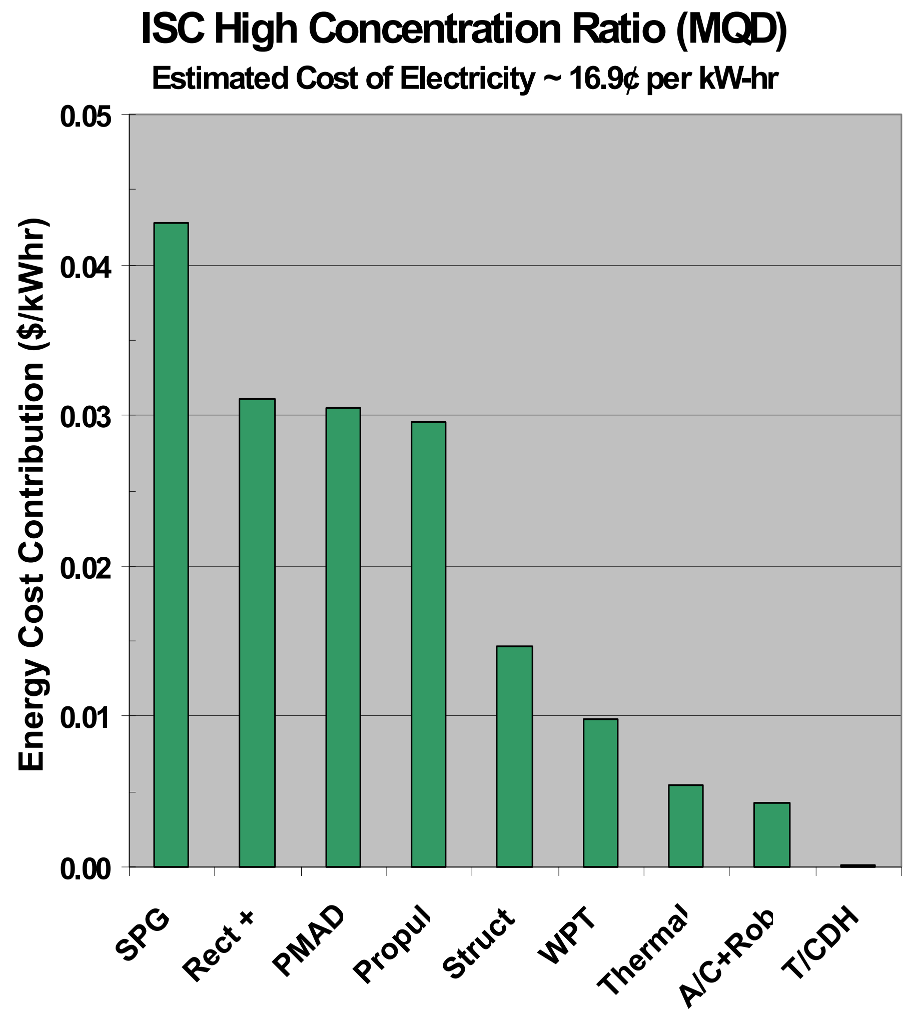
Estimated Cost of Electricity ~ 22.8¢ per kW-hr



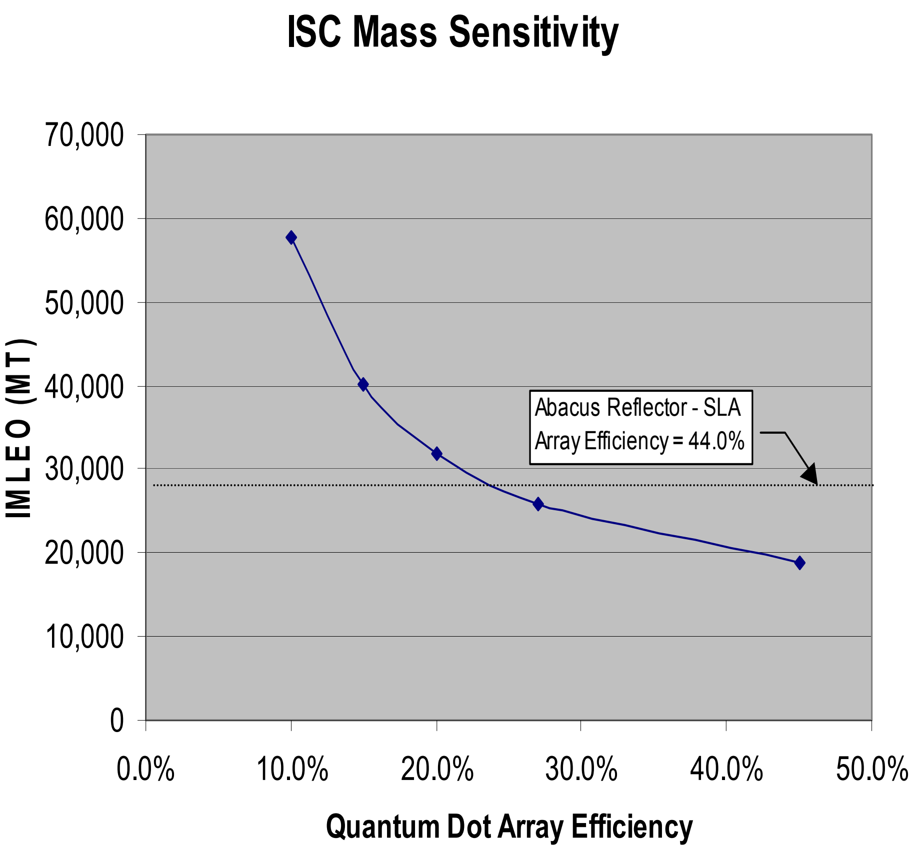
SCTM Systems Integration, Analysis and Modeling

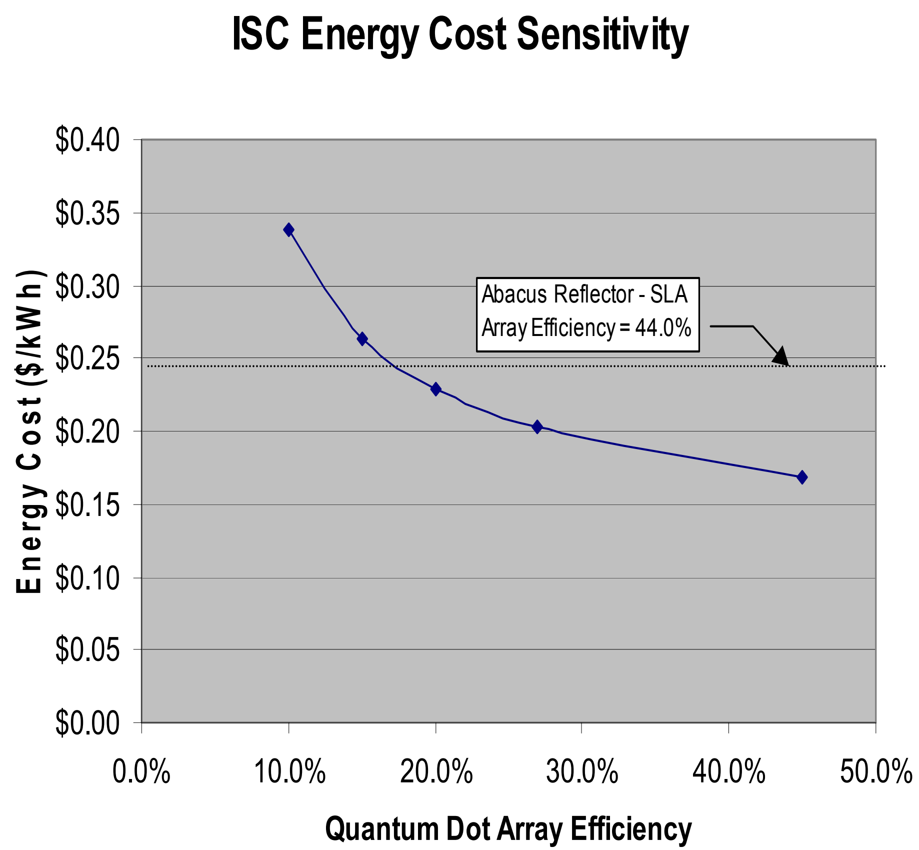
SERT Results: Subsystem Contributions to Energy Cost (2 of 2)





SCTM Systems Integration, Analysis and Modeling
ISC Sensitivity to Quantum Dot Array Efficiency





SCTM Systems Integration, Analysis and Modeling

SERT Conclusions

Concept Definition

- New configurations that eliminate power-conducting slip rings have been identified
- Minimum PMAD configurations, motivated by large PMAD masses, have been identified
- Alternative options include Halo constellations for both RF and laser WPT, solar dynamic configurations, and SunTower derivatives, as well as others
- NRA technologies have been integrated into concepts and models, where appropriate
- Distributed laser-based WPT configurations are very promising

Modeling and Analysis

- Most promising RF configurations to date are:
  - ISC: lightest, most cost-effective, but requiring advanced PV or thermal managment technology
  - Abacus Reflector: modular assembly/maintenance, moderate energy cost, but reflector issues exist
  - Sun Tower: easiest assembly and control, but highest energy cost due to shadowing
- Orbit transfer propulsion, solar power generation, PMAD and ground systems are the primary contributors to SSP delivered energy costs.
- SSP system size and cost are most sensitive to WPT and SPG efficiencies.
- Configurations delivering 1.2 GW have an energy cost range of 17¢-32¢/kWhr, which can be reduced by approximately 1¢-2¢/kWhr by delivering higher power densities per satellite
- Under current pricing assumptions, self-transfer of SSP payloads from LEO to GEO is more cost-effective than a purchased space transportation service
- Advanced technology SEP systems offer an excellent non-nuclear transportation alternative for HEDS missions to the Moon and Mars.

CURRENT SYSTEM INTEGRATION ACTIVITIES FOR SCTM AND TITAN

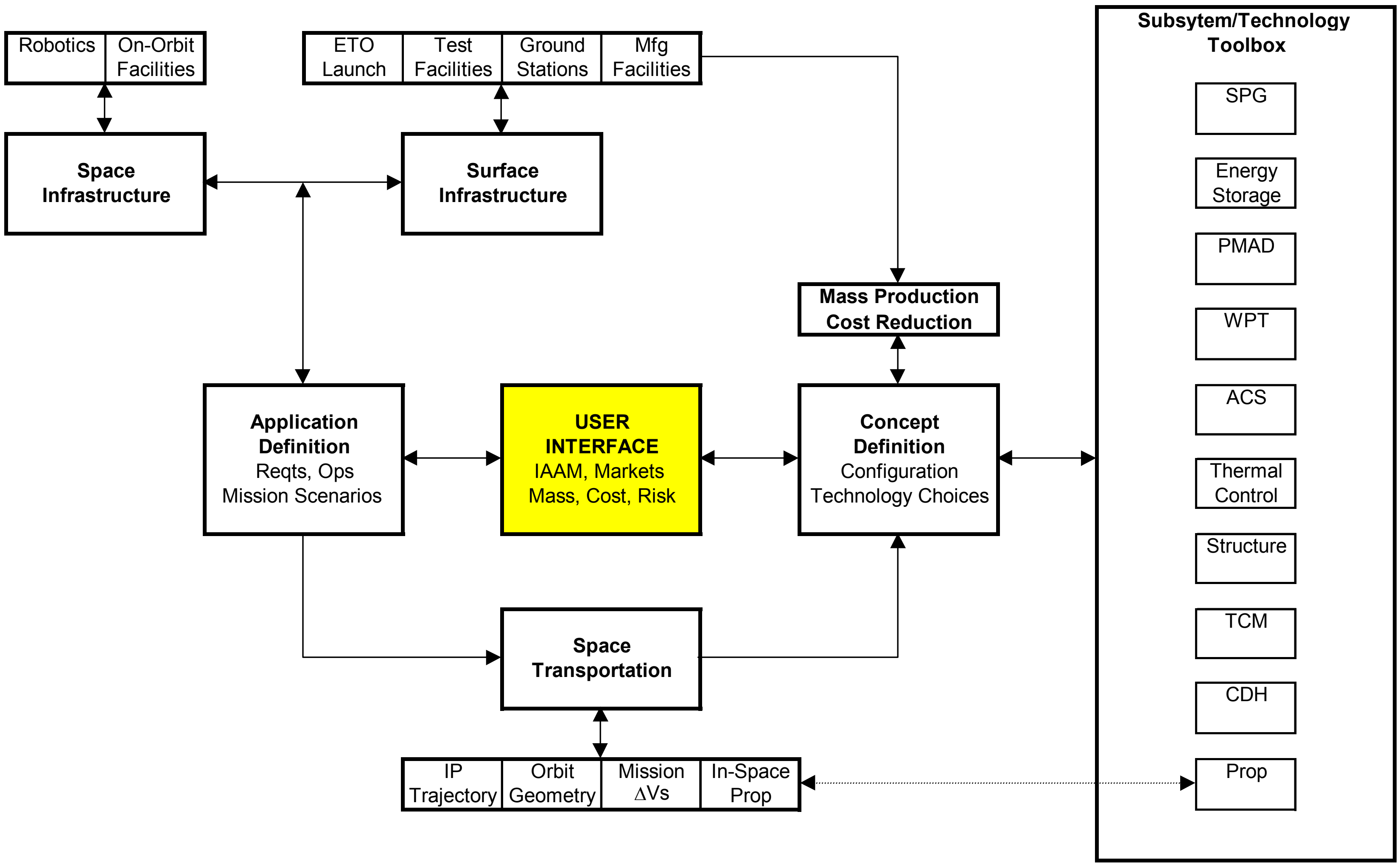
Summary of Ongoing System Integration Activities

- **Activities and Accomplishments**
  - Proposed new SSM architecture which has since become basis for more comprehensive TITAN Model architecture
  - Restructuring SSM for inclusion in TITAN
  - Updating SSM subsystem worksheets: Thermal, Structures, SPG, PMAD, WPT, Attitude Control
  - Modeling Aerospace and Boeing Laser SSP concepts for SSM/TITAN
  - Supporting TFD concept development and modeling efforts
  - Participation in SCTM working group telecons
  - Evaluation of new SSP concepts and configurations (e.g. HotDot Array)
- **Issues**
  - Response to NRC requires higher fidelity modeling & peer review
  - Industry participation in SIWG limited by SCTM program delays
  - Need data to support laser system modeling
  - Approach to cost estimation (data and models to be used) still unclear

BACKUP CHARTS

SCTM Systems Integration, Analysis & Modeling

Proposed New Modeling Architecture for SSM



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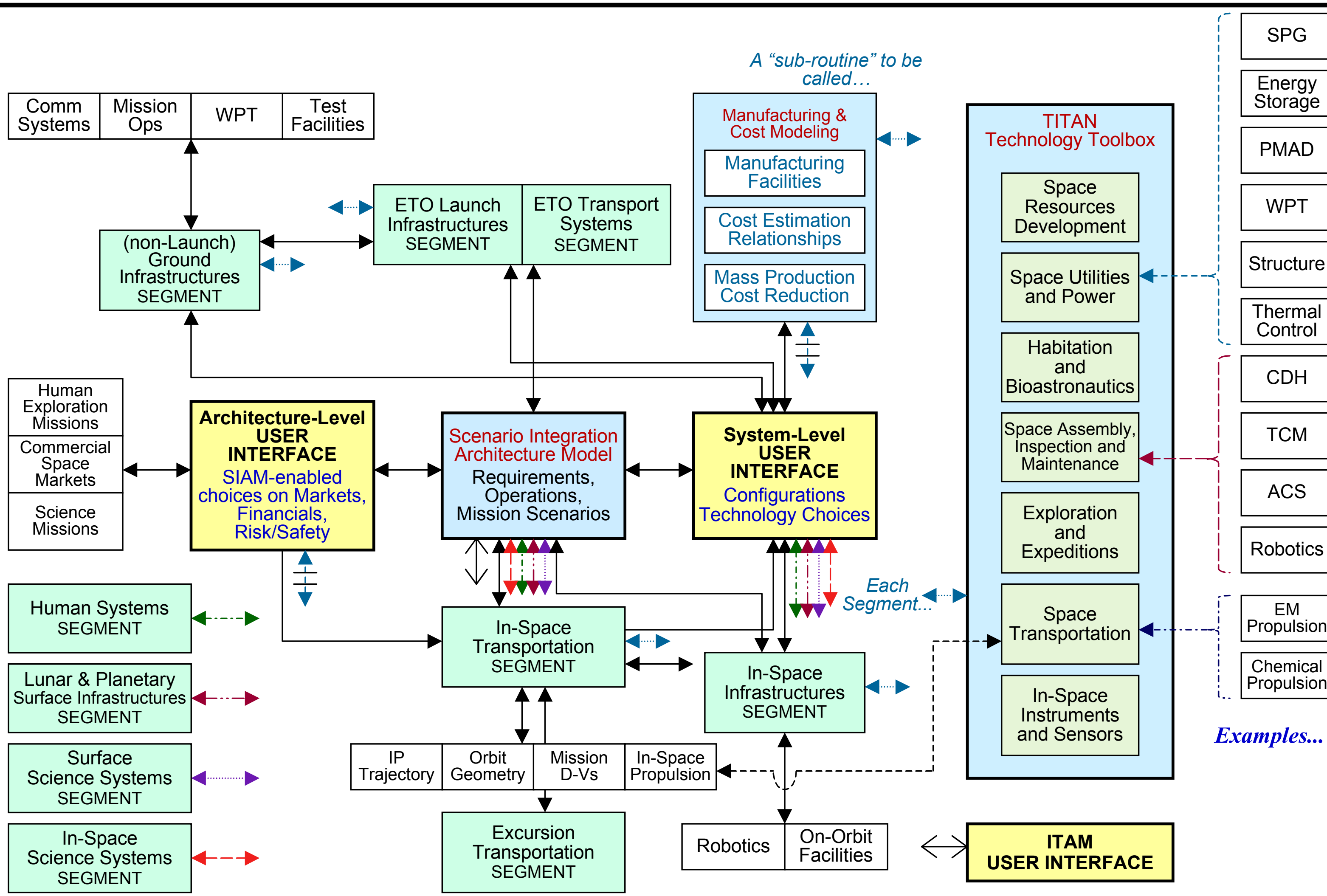
THREADS Integrated Technology ANalysis (TITAN) ModelArchitecture Overview



Model Description

- TITAN (THREADS Integrated Technology ANalysis) is a Microsoft Excel-based model, currently under development, that will use a modular, multi-workbook environment to quantitatively evaluate how technology choices and/or investment decisions impact the broad spectrum of HEDS systems, missions and architectures, in terms of performance, cost and risk.
- To provide a consistent basis of existing and projected technology information for use in these evaluations, TITAN will employ a technology "toolbox" based on the THREADS technology database, and by design, the user will be able to select and apply technology performance data from the toolbox, across the full range of modeled systems and missions.
- In essence, the TITAN modeling approach is designed to allow the user to "build" a mission architecture by selecting a complete set of modeled system elements from various architecture segments such as ETO Transportation Systems, Space Transportation, In-Space Infrastructure, In-Space Science, Surface Science, etc.; developing an integrated mission scenario/timeline; and selecting the system technologies to be examined, from the technology toolbox.
- Although TITAN will be specifically designed to accommodate HEDS applications, it is expected that the model will be capable of performing similar evaluations for various Earth and space science missions as well as missions for commercial space markets.

Functional Descriptions
The "TITAN Technology Tool Box" (T3B)

TITAN Technology Toolbox

- Space Resources Development
- Space Utilities and Power
- Habitation and Bioastronautics
- Space Assembly, Inspection and Maintenance
- Exploration and Expeditions
- Space Transportation
- In-Space Instruments and Sensors

- **The TITAN "Technology Tool Box" (T3B) will be the primary repository for information concerning the wide array of potential technologies that might be applied in future systems -- including quantitative metrics with which options for incorporation can be assessed**
- **The T3B will provide a common "look-up table" of information concerning various technologies**
- **The T3B provides information on many different technologies…**
  - Assuring that within an analysis that the same level of technology advancement is used (or if different levels are used, that these are deliberate choices…
- **And in several timeframes, including State of the Art; Immediate Future; Mid-Term; Far-term; and Very Far-term**
- **The T3B supports Technical / Performance modeling; Cost / Economic modeling; and, Technology Assessment**
- **T3B will be organized according to the Work Breakdown Structure (WBS) of the THREADS ("Technology for Human/Robotic Exploration and Development of Space") taxonomy**

Functional Descriptions
TITAN In-Space Infrastructure Segment (ISIS)

Non-Launch Infrastructure Ground SEGMENT

Launch Ground Infrastructure SEGMENT

Launch Vehicle SEGMENT

In-Space Transportation SEGMENT

In-Space Infrastructure SEGMENT

Surface Systems SEGMENT

Science Systems SEGMENT

Human Systems SEGMENT

- **The TITAN In-Space Infrastructure Segment (ISIS) will enable modeling at a strategic level of the choices of space-based infrastructure associated with the broad spectrum of HEDS mission architectures and scenarios.**
- **ISIS will rely on the T3B for information concerning the wide array of potential technologies that might be applied in future systems -- including quantitative metrics with which options for incorporation can be assessed.**
- **ISIS will possess the flexibility to model an unlimited number of different functional systems or subsegments, representing various infrastructure elements such as SSP, Fuel Depots, Gateway, Assembly Nodes, ISS, Communication Satellites, etc.**
- **ISIS will also be able to accommodate different user-defined configurations for each system/subsegment.**
- **ISIS will interface directly with SIAM to pass information to and from the System-Level User Interface (SUI), the Architecture-Level User Interface (AUI) and the other TITAN segments.**
- **ISIS will rely on SUI to specify system performance requirements, configuration, and technology choices for each subsegment; and on the AUI for mission scenario/architecture information, i.e., subsegments to be used and their number, orbits, timing, data needed from related segments, etc.**
- **ISIS will be able to provide outputs such as mass breakdowns, development costs, and parameter data for sensitivity studies directly to the user or to the user interfaces via SIAM.**

SCTM Systems Integration, Analysis and Modeling

SIWG Near-Term Plans

- **Modeling Activities**
  - Update SSM Subsystem Worksheets as Needed
  - Model Boeing/Aerospace Laser Configurations
  - Complete Conversion of SSM to New (TITAN) Modeling Architecture
  - Enable Use of THREADS Technology Database in Models
  - Identify a Preferred Cost Estimation Approach for Model.
  - Model and Evaluate Selected New Concepts (e.g. HotDot, Solar-Pumped Laser Concepts, etc.)
  - Work with SCTM Program Management to Address NRC Recommendation for Model Peer Review

- **Systems Integration Activities**
  - Resume Regularly Scheduled (Monthly) SIWG Telecon
  - Contribute Information to other SSP Telecons, e.g., WPT, TFD
  - Disseminate Systems and Analysis Information to R&TWG's
  - Obtain Technology Information as Needed from R&TWG's
  - Participate in Concept Development and Selection Activities