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Space Systems Architecture
Lecture 3
Introduction to
Tradespace Exploration

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Metis Design

Space Systems, Policy, and Architecture Research Consortium
A joint venture of MIT, Stanford, Caltech & the Naval War College
for the NRO

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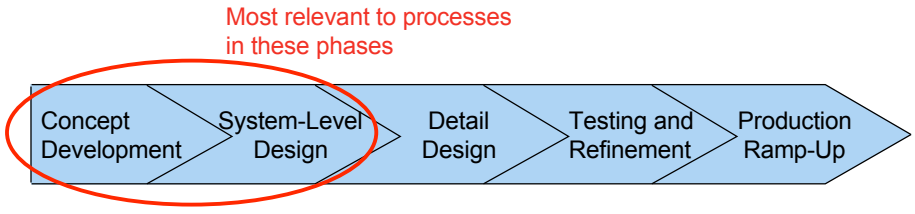
Tradespace Exploration

- A process for understanding complex solutions to complex problems
- Allows informed "upfront" decisions and planning



Phases of Product Development

From Ulrich & Eppinger, ***Product Design and Development***, 1995

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Architecture Trade Space Exploration

A process for understanding complex solutions to complex problems

- Model-based high-level assessment of system capability
- Ideally, *many* architectures assessed
- Avoids optimized *point solutions* that will not support evolution in environment or user needs
- Provides a basis to explore technical and policy *uncertainties*
- Provides a way to assess the value of *potential* capabilities

Allows informed “upfront” decisions and planning

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Integrated Concurrent Engineering

A process creating preliminary designs very fast

- State-of-the-art rapid preliminary design method
- Design tools linked both electronically and by co-located humans
- Design sessions iterate/converge designs in hours
- Requires ready tools, well poised requirements

Allows rapid reality check on chosen architectures
Aids transition to detailed design

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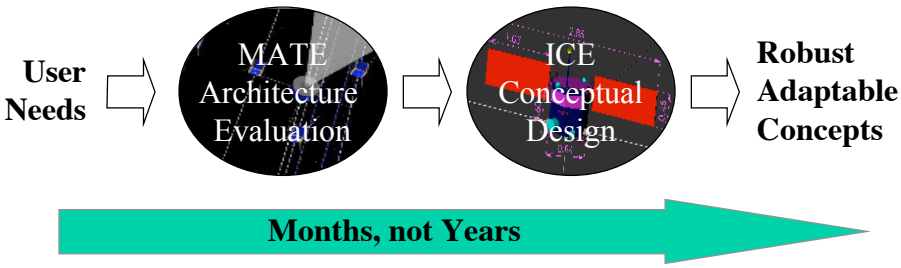
Emerging Capability

- Linked method for progressing from vague user needs to conceptual/preliminary design very quickly
- MANY architectures, several/many designs considered
- Understanding the trades allows selection of robust and adaptable concepts, consideration of policy, risk.



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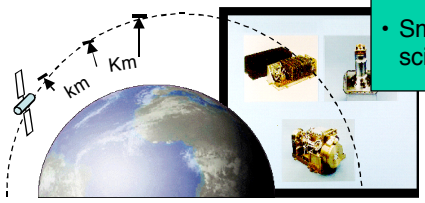
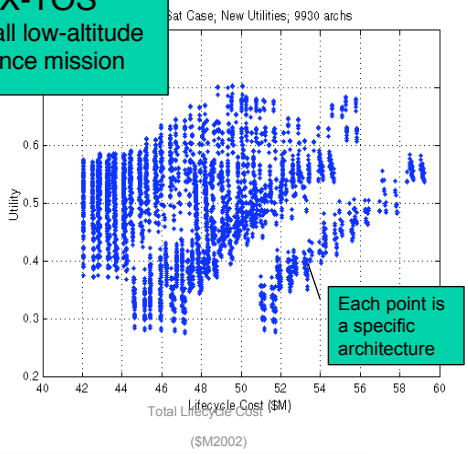
What is an Architecture Trade Space?



X-TOS
- Small low-altitude science mission



DESIGN VARIABLES: The architectural trade parameters

- Orbital Parameters
  - Apogee altitude (km) 150-1100
  - Perigee altitude (km) 150-1100
  - Orbit inclination 0, 30, 60, 90
- Physical Spacecraft Parameters
  - Antenna gain
  - communication architecture
  - propulsion type
  - power type
  - delta_v

Assessment of the utility and cost of a large space of possible system architectures

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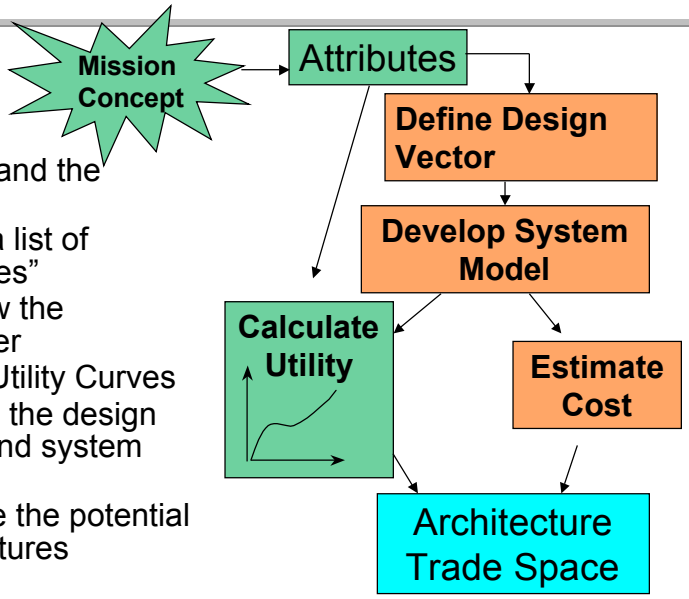
Developing A Trade Space

- Understand the Mission
- Create a list of "Attributes"
- Interview the Customer
- Create Utility Curves
- Develop the design vector and system model
- Evaluate the potential Architectures



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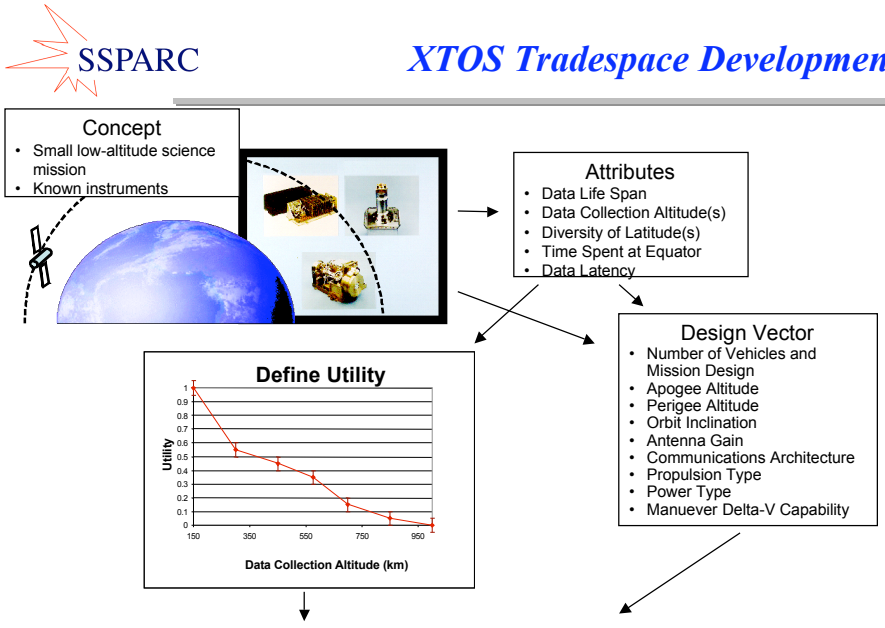
XTOS Tradespace Development



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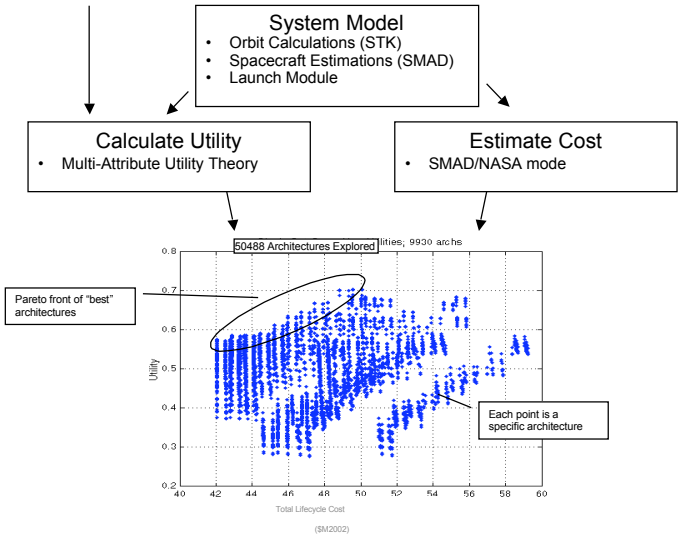

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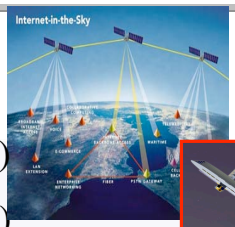
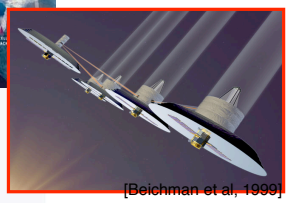
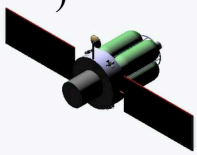
Understanding What Systems Do

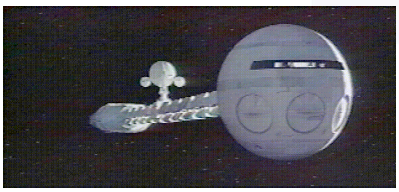
- Transmit Information
- Collect Information
- Move Mass (inc. People)
- Others (Space Station…)

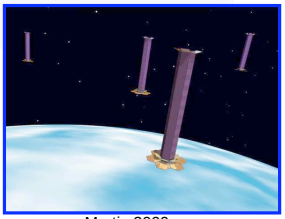




[Beichman et al, 1999]







Martin 2000

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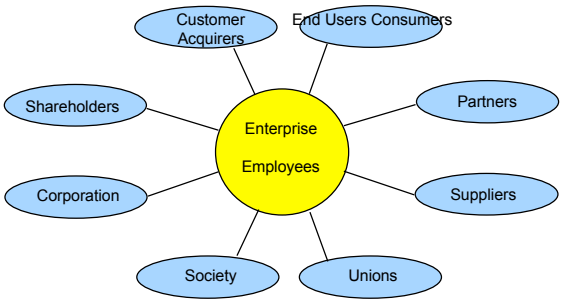
Understanding who cares - Stakeholders

- Many interested parties in a complex system
- Each "customer" has a set of needs
- They are different, and can be contradictory



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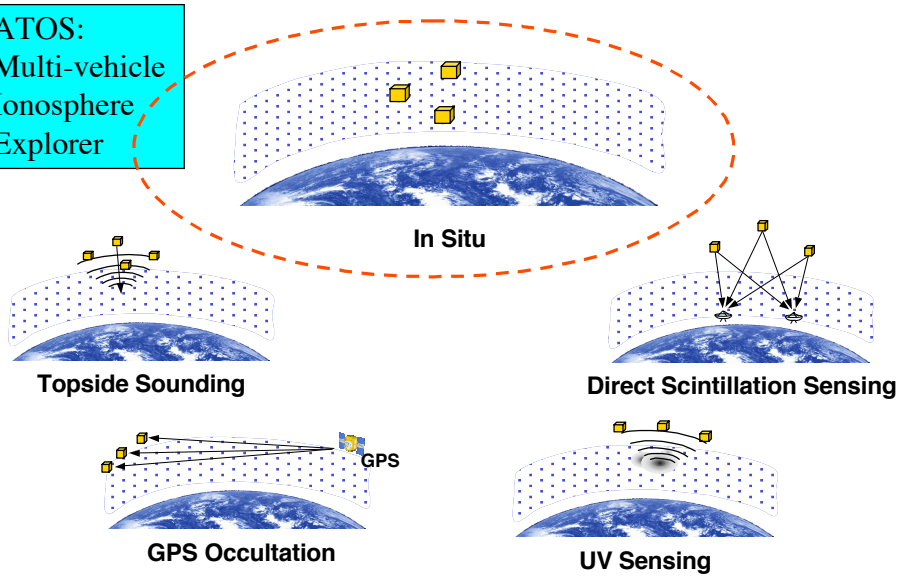
Concept Selection: Bounding

ATOS:
Multi-vehicle
Ionosphere
Explorer



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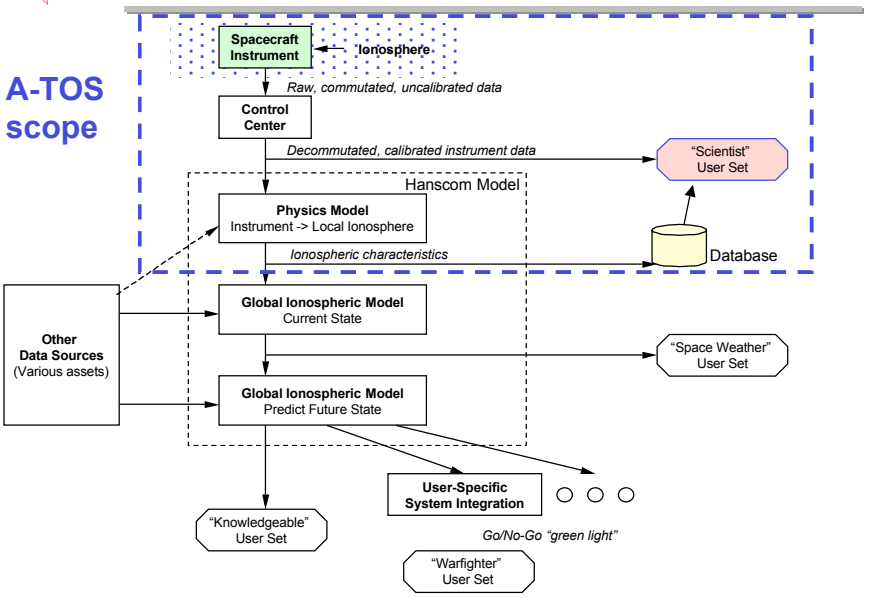
Scoping



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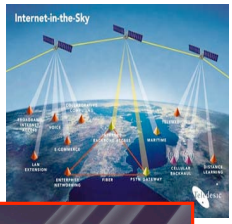
Attributes

- "what the decision makers need to consider"
- (and/or what the user truly cares about)
- Examples: Billable minutes = GINA metrics
- TPF Pictures = camera performance metrics
- Rescue/move satellites = mass moving, grappling capability, timeliness
  - Could have sub-cartoons for above



[Beichman et al, 1999]

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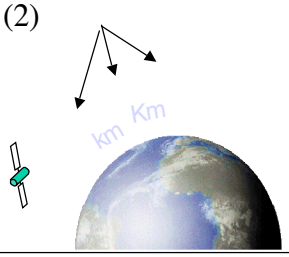
XTOS Attributes

1) Data Life Span
2) Data Altitude
3) Maximum Latitude
4) Time Spent at Equator
5) Data Latency

(1)

(2)



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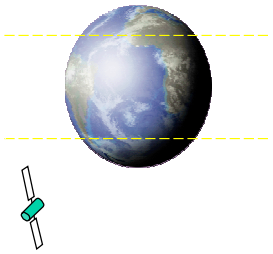

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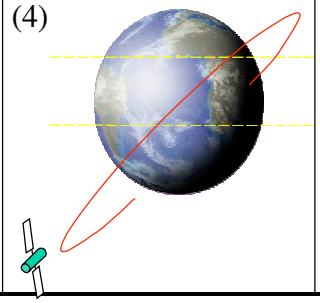

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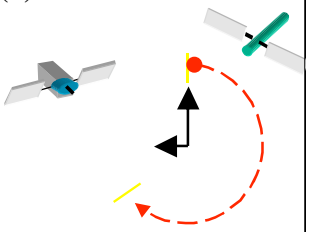

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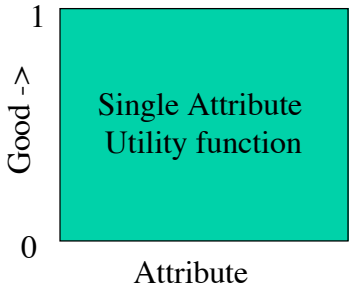
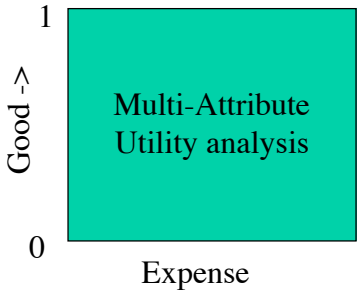
Utilities

- "What the attributes are WORTH to the decision makers"
- Single Attribute utility maps attribute to utility
- Multi-attribute utility maps an architecture (as expressed by its attributes) to utility





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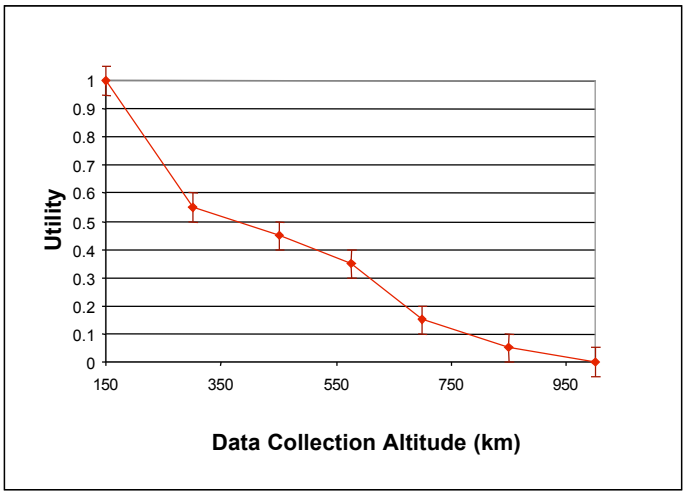
Single Attribute Utilities



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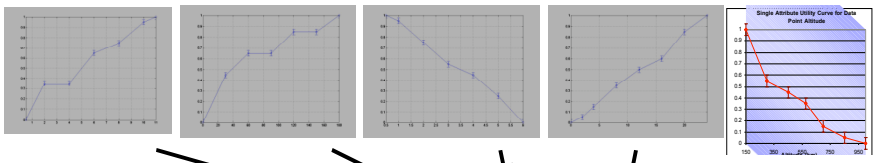
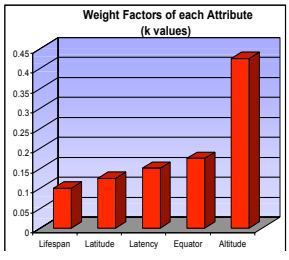
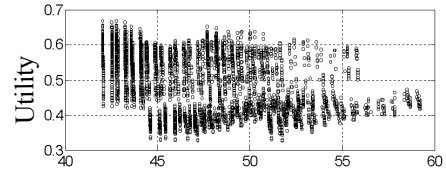
Multi-Attribute Utility



$$KU(\underline{X})+1=\prod_{i=1}^{N}\left(Kk_iU(X_i)+1\right)$$





Total Lifecycle Cost ($M 2002)

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XTOS Design Vector

- "Parameters of the Trade Space"

Variable:	First Order Effect:
Orbital Parameters:	
•Apogee altitude (200 to 2000 km)	Lifetime, Altitude
•Perigee altitude (150 to 350 km)	Lifetime, Altitude
•Orbit inclination (0 to 90 degrees)	Lifetime, Altitude
	Latitude Range
	Time at Equator
Physical Spacecraft Parameters:	
•Antenna gain (low/high)	Latency
•Comm Architechture (TDRSS/AFSCN)	Latency
•Propulsion type (Hall / Chemical)	Lifetime
•Power type (fuel / solar)	Lifetime
•Total ΔV capability (200 to 1000 m/s)	Lifetime

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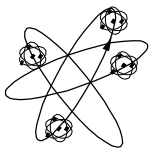
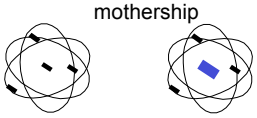
ATOS design Vector

- Geometry of the Multi-vehicle Swarm

Swarm Orbit Parameters

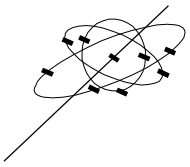


Mothership/ no mothership



Number of spacecraft in swarm

Geometry of swarm



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Scoping-QFDs

Attributes	Perigee	Apogee	Delta-V	Propulsion	Inclination	Comm System	Ant. Gain	Rower system	Mission Scenario	Total Impact
Design Vars										
Data Lifespan	9	9	9	6	0	0	0	6	9	48
Sample Altitude	9	9	0	0	0	0	0	0	9	27
Diversity of Latitudes	0	0	0	0	9	0	0	0	9	18
Time at Equator	0	6	0	0	9	0	0	0	9	24
Latency	3	3	0	0	3	9	9	6	3	36
Total	21	27	9	6	21	9	9	12	39	
Cost	9	9	3	6	6	3	6	6	9	
Total w/Cost	30	36	12	12	27	12	15	18	48	

Identify key interactions for modeling

Sums identify attributes and Design Variables that are likely to be (or not be) distinguishers

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Scoping-Iteration/evolution

TABLE II. EVOLUTION OF DESIGN VECTOR

First Cut	After GINA exercise	After utility characterization and module progress	Schedule Crunch
10/20/00	10/31/00	1/15/01	1/21/01
Swarm type	Concept type	Swarm perigee altitude	Swarm perigee altitude
# sats/swarm	# sats/swarm	Swarm apogee altitude	Swarm apogee altitude
# swarms	# swarms per plane	# sats/swarm	# sats/swarm
Swarm orbit	# orbital planes	# subplanes/swarm	# subplanes/swarm
Intra-swarm orbit	Swarm altitude	# suborbits/subplane	# suborbits/subplane
Instrument type	Swarm orientation	Yaw angle of subplanes	Yaw angle of subplanes
# instruments/sat	Swarm geometry	Max sat separation	Max sat separation
TT&C scheme	Separation within swarm	Mothership (yes/no)	
Ground station	Mothership (yes/no)		
Mission lifetime			
Processing scheme			
Position control scheme			
Latitude of interest			

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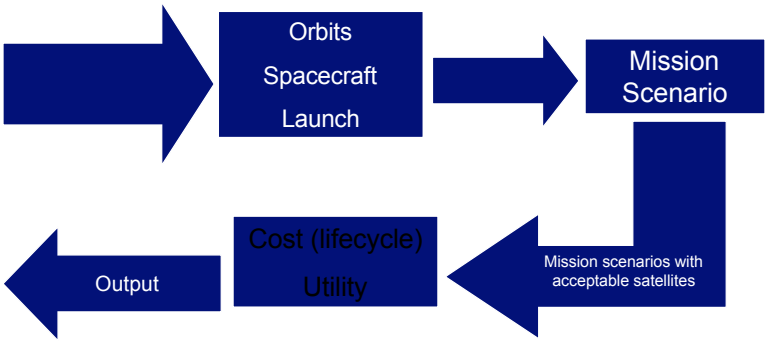
Mapping Design Vector to Attributes and Utilities - Simulation Models

XTOS Simulation Software Flow Chart



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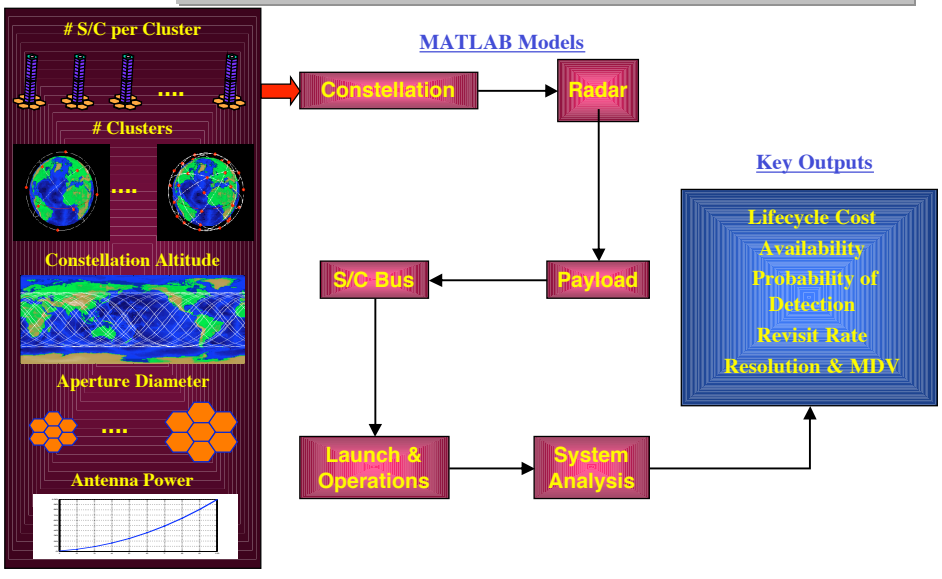
Techsat Models



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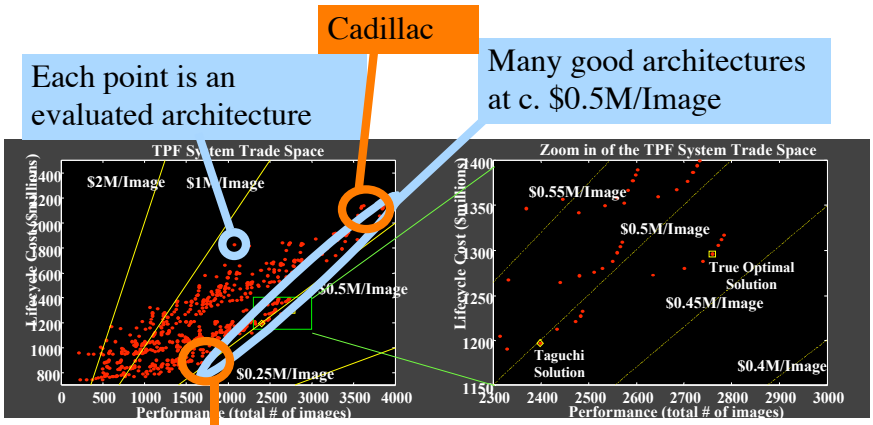
Exploring the Tradespace



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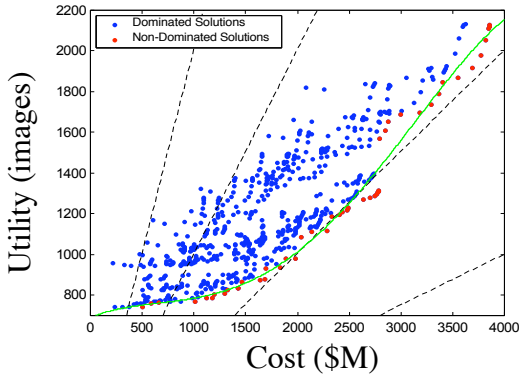
The Pareto Front

- Set of "best" solutions
- "Dominated" solutions are more expensive or less capable



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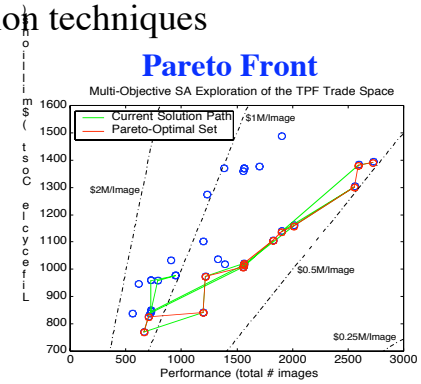
Optimization

- Can look for the Pareto front using advanced optimization techniques

Pareto Front



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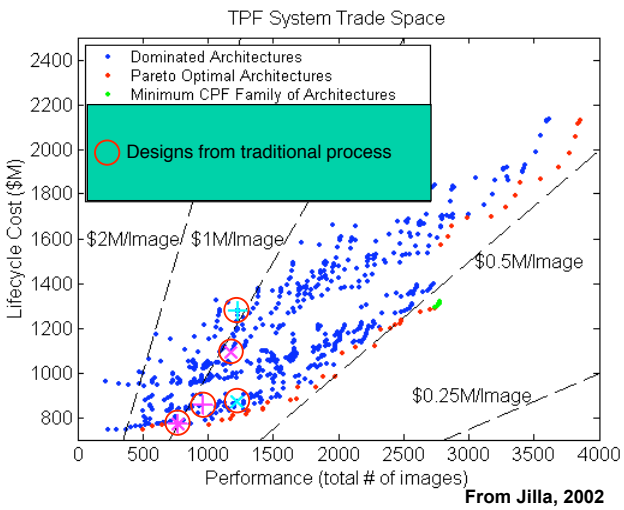
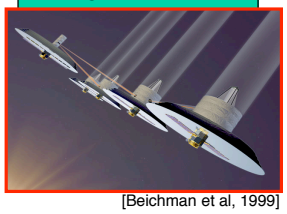
Using the Trade Space to Evaluate Point Designs



From Jilla, 2002

TPF

- Terrestrial Planet Finder - a large astronomy system
- Design space: Apertures separated or connected, 2-D/3-D, sizes, orbits
- Images vs. cost



[Beichman et al, 1999]

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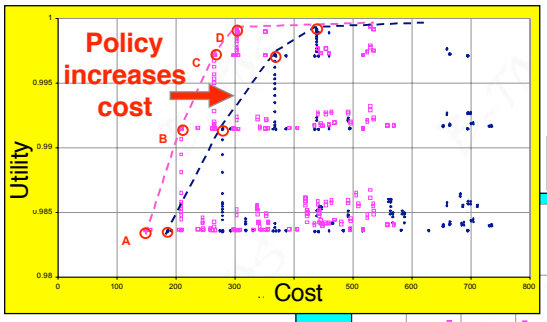
Using Architecture Models to Understand Policy Impacts

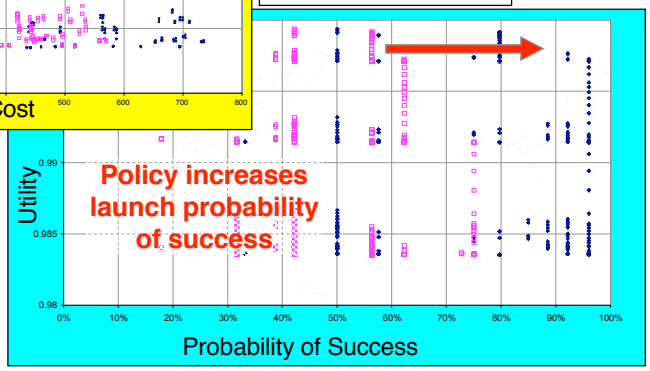


100% of B-TOS architectures have cost increase under restrictive launch policy for a minimum cost decision maker

- *Restrictive launch policy*
- *Unrestrictive launch policy*

B-TOS

- Swarm of small sats. doing observation
- Utility for multiple missions



From Weigel, 2002

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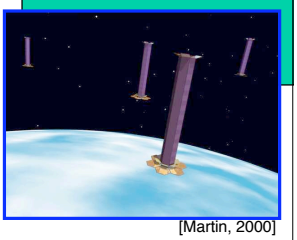
Using Architecture Models to Consider Uncertainty

TechSat

- Constellation of satellites doing observation of moving objects on the ground
- Uncertainties driven by instrument performance/cost



[Martin, 2000]

From Walton, 2002

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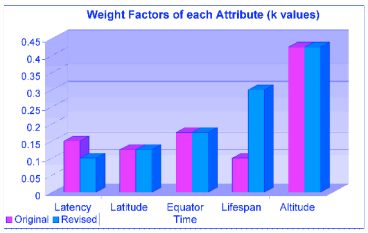
Changes in User Preferences Can be Quickly Understood

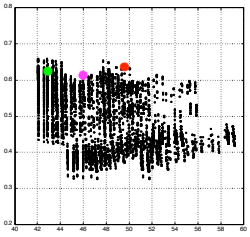


Architecture trade space reevaluated in less than one hour

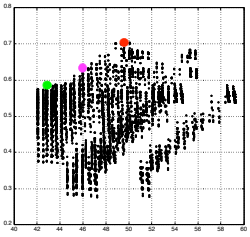
User changed preference weighting for lifespan

X-TOS

Original



Revised



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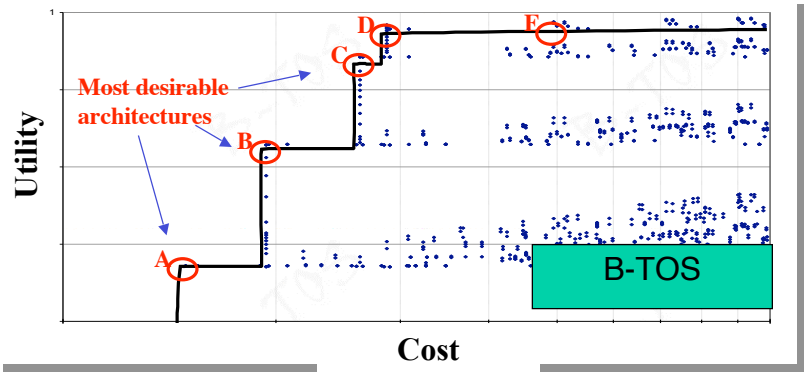
Assessing Robustness and Adaptability

- Pareto front shows trade-off of accuracy and cost
- Determined by number of satellites in swarm
- Could add satellites to increase capability



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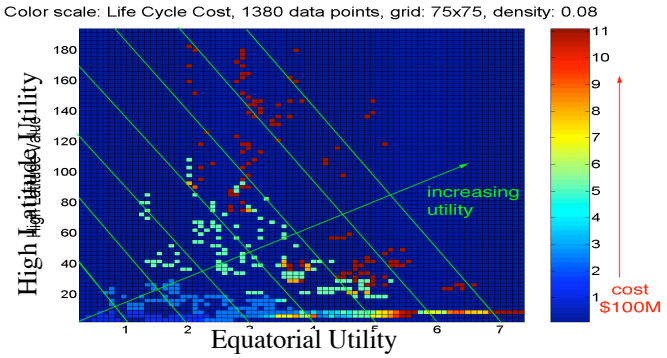
Questioning User Desires

- Best low-cost mission do only one job well
- More expensive, higher performance missions require more vehicles
- Higher-cost systems can do multiple missions
- Is the multiple mission idea a good one?

A-TOS
- Swarm of very simple satellites taking ionospheric measurements
- Several different missions



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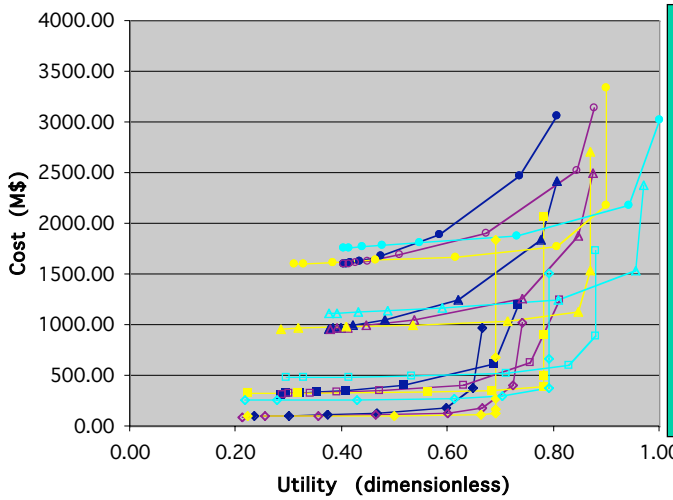
Understanding Limiting Physical or Mission constraints



SPACETUG
- General purpose orbit transfer vehicles
- Different propulsion systems and grappling/observation capabilities
- Lines show increasing fuel mass fraction

Hits a "wall" of either physics (can't change!) or utility (can)

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Integrated Concurrent Engineering (ICE)

- ICE techniques from Caltech and JPL
- Linked analytical tools with human experts in the loop
- Very rapid design iterations
- Result is conceptual design at more detailed level than seen in architecture studies
- Allows understanding and exploration of design alternatives
- A reality check on the architecture studies - can the vehicles called for be built, on budget, with available technologies?

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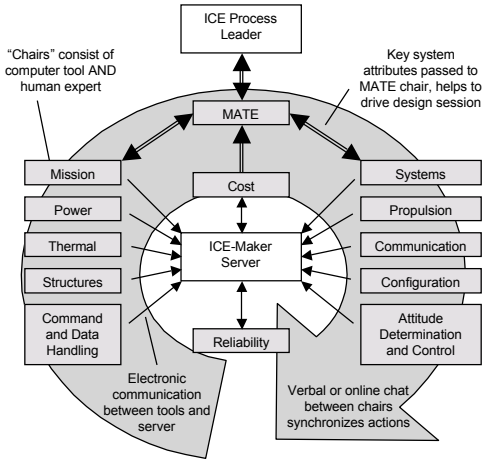
ICE Process (CON with MATE)



- Directed Design Sessions allow very fast production of preliminary designs
- Traditionally, design to requirements
- Integration with MATE allows *utility* of designs to be assessed real time

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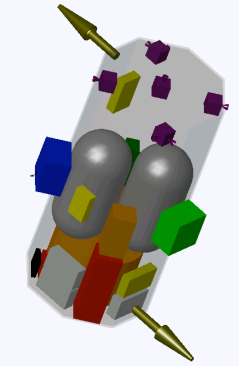
ICE Result - XTOS Vehicle



- Early Designs had excessively large fuel tanks and bizarre shapes
- Showed limits of coarse modeling done in architecture studies
- Vehicle optimized for best utility - maximum life at the lowest practical altitude

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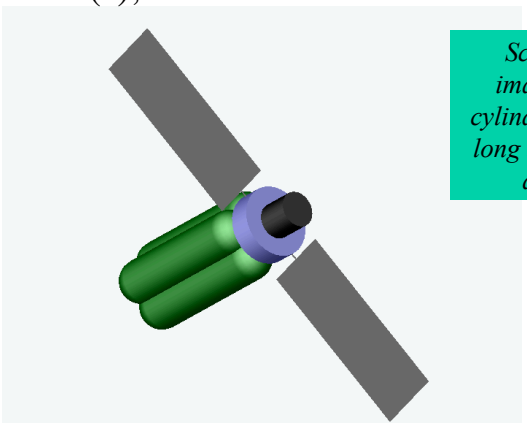
SPACETUG Biprop One-Way GEO Tug

- 1312 kg dry mass, 11689 kg wet mass
- Quite big (and therefore expensive); not very practical (?);



Scale for all images: black cylinder is 1 meter long by 1 meter in diameter

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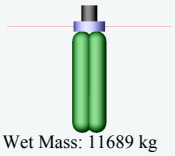
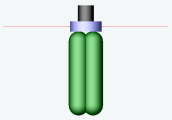
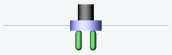
SPACETUG Tug Family (designed in a day)

Bipropellant	Cryogenic
	
Wet Mass: 11689 kg	Wet Mass: 6238 kg
Electric – One way	**Electric – Return Trip**
	
Wet Mass: 997 kg	Wet Mass: 1112 kg

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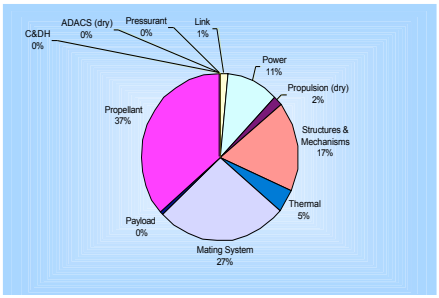
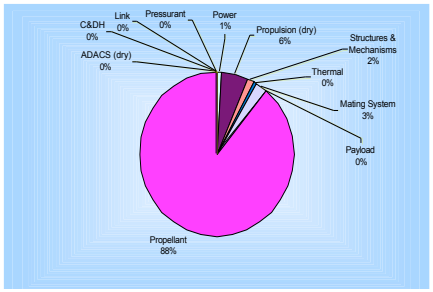
Learning from the ICE results: Mass Distribution Comparison



Electric Cruiser



Biprop one-way

- Low ISP fuel requires very large mass fraction to do mission
- Other mass fractions reasonable, with manipulator system, power system, and structures and mechanisms dominating

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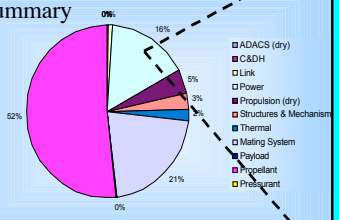
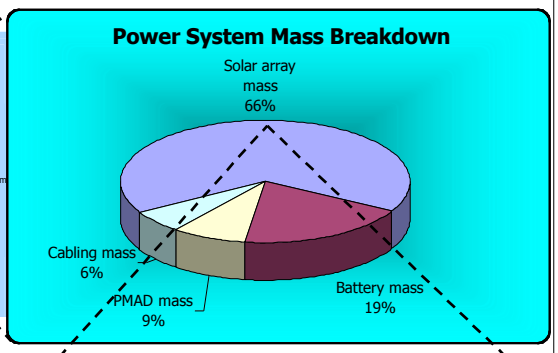
More Than Mass Fractions

LEO Tender 1
mass summary





Select solar array material:	Triple Junction (InGaP/GaAs/Ge)	
Minimum efficiency	24.5	%
Maximum efficiency	28.0	%
Nominal temperature	28.0	C
Temperature loss	0.5	%/deg C
Performance degredation	2.6	% / year
Minimum temperature	0.5	C
Maximum temperature	85.0	C
Energy density	25.0	W / kg
Solar array mass	150.6685167	kg
Total solar array area	9.965098159	m^2
# of solar arrays	2	#
Individual solar array area	4.98254908	m^2

Detailed information can be drawn from subsystem sheets, including efficiencies, degradations temperature tolerances, and areas

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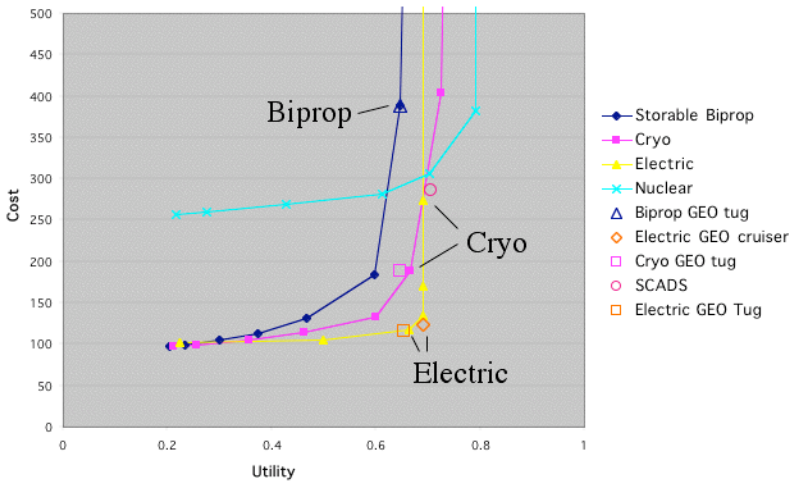
Trade Space Check



The GEO mission is near the "wall" for conventional propulsion

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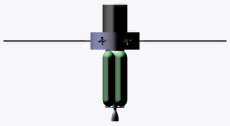
SPACETUG LEO Tender Family

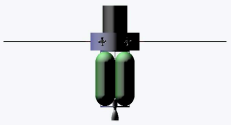
LEO 1 - 1404 kg wet

LEO 2 - 1242 kg wet

LEO 4 - 1782 kg wet



LEO 4A - 4107 kg wet



Tenders

- Orbit transfer vehicles that live in a restricted, highly populated set of orbits
- Do low Delta-V transfers, service, observation

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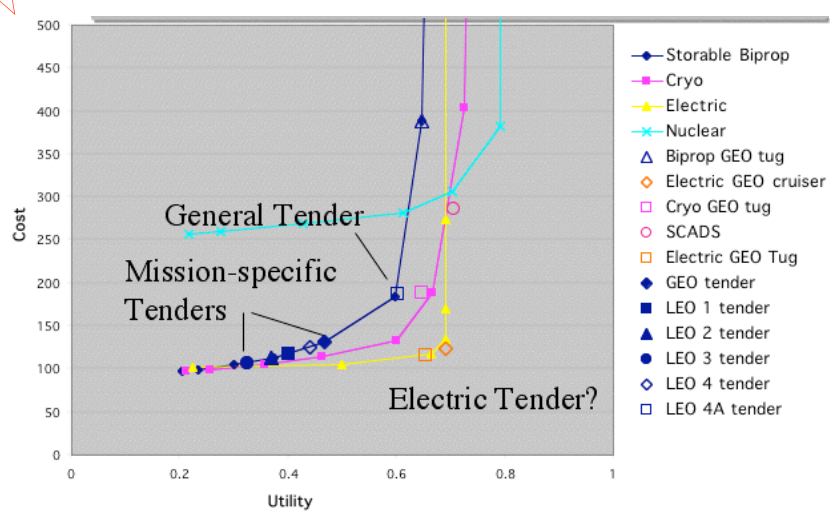
Tenders on the tradespace



The Tender missions are feasible with conventional propulsion

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What you will learn

- Trade space evaluation allows efficient quantitative assessment of system architectures given user needs
- State-of-the-art conceptual design processes refine selected architectures to vehicle preliminary designs
- Goal is the right system, with major issues understood (and major problems ironed out) entering detailed design

Emerging capability to get from user needs to robust solutions quickly, *while considering full range of options, and maintaining engineering excellence*