Space Systems Architecture
Lecture 3
Introduction to Tradespace Exploration

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

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

Integrated Concurrent Engineering

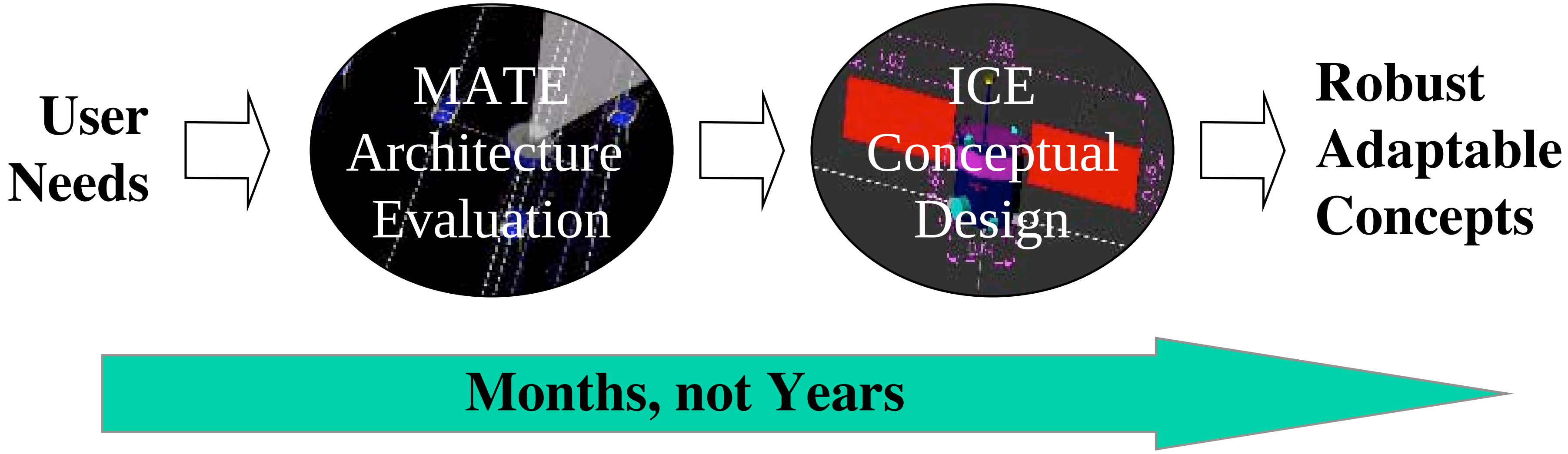
A process creating preliminary designs very fast

- 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

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.



User Needs

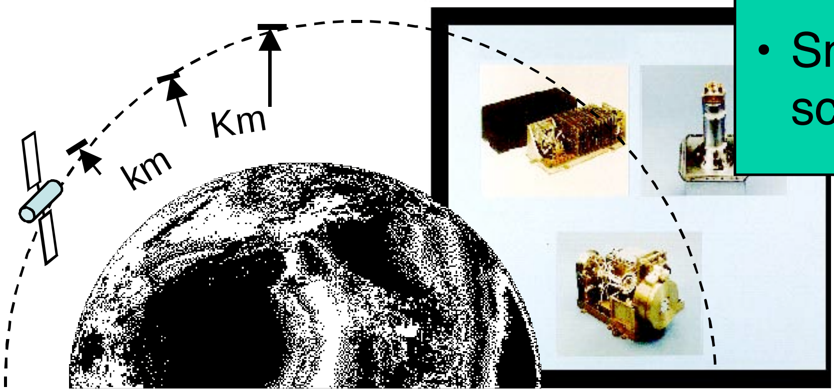
MATE Architecture Evaluation

ICE Conceptual Design

Robust Adaptable Concepts

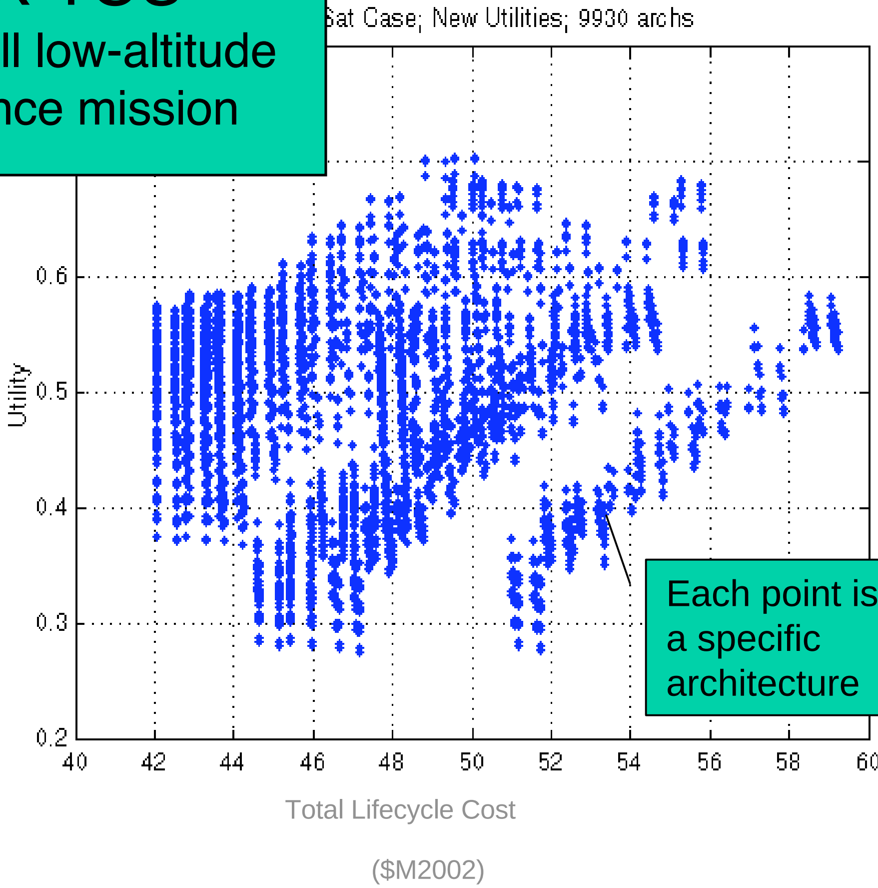
Months, not Years

What is an Architecture Trade Space?



X-TOS

- Small low-altitude science mission



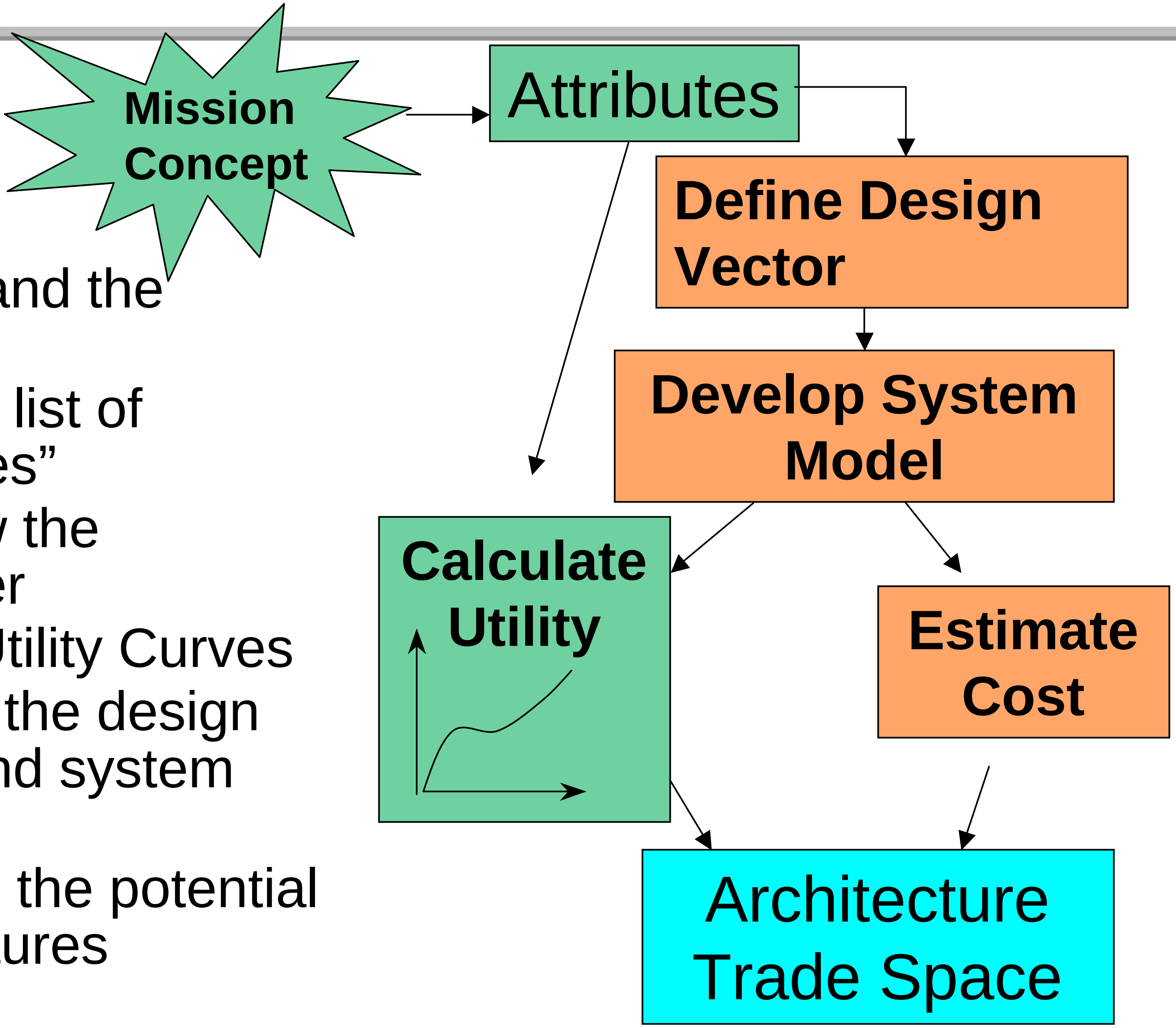
Each point is a specific architecture

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

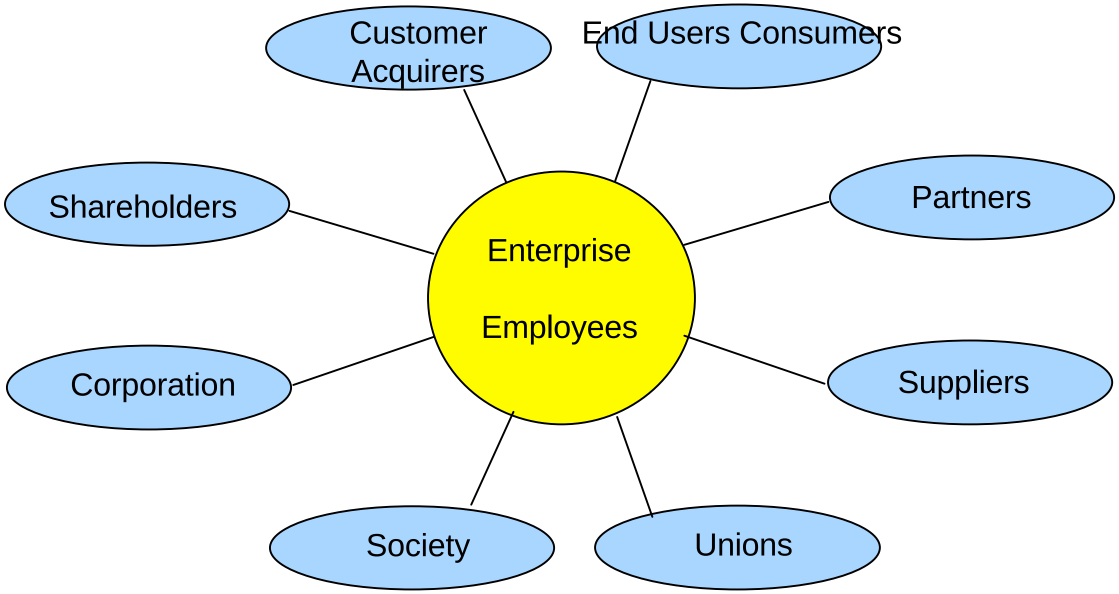
Developing A Trade Space



- 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

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



Customer Acquirers

End Users Consumers

Shareholders

Partners

Enterprise

Employees

Corporation

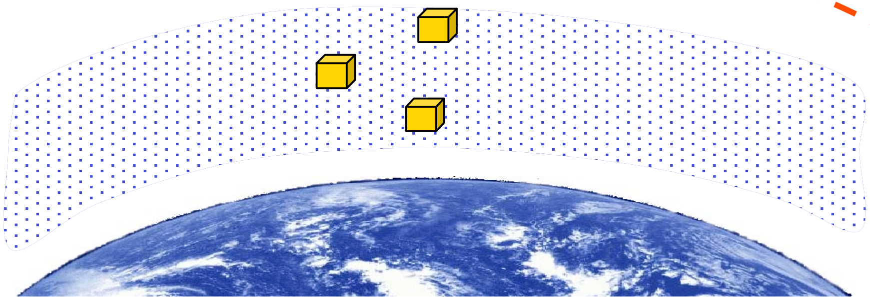
Suppliers

Society

Unions

Concept Selection: Bounding

ATOS:
Multi-vehicle
Ionosphere
Explorer



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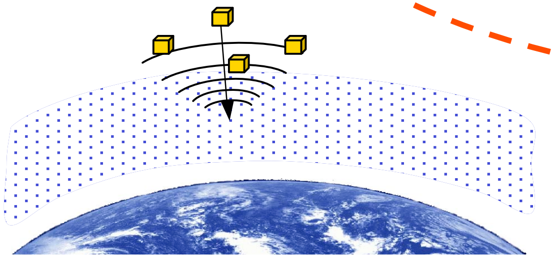
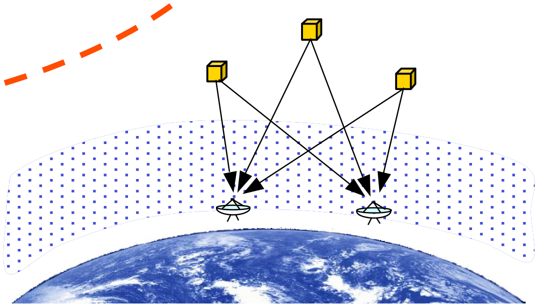
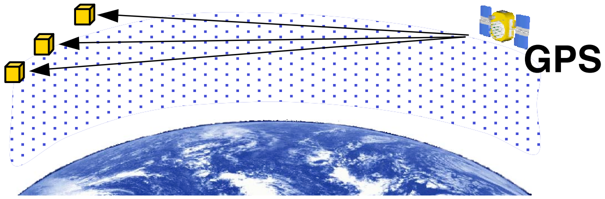


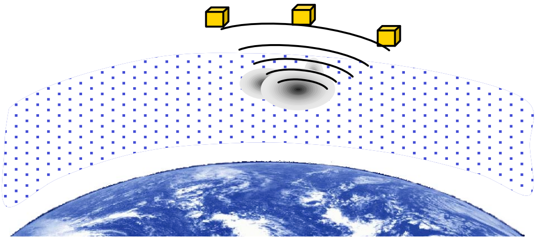
Topside Sounding



Direct Scintillation Sensing



GPS Occultation



UV Sensing

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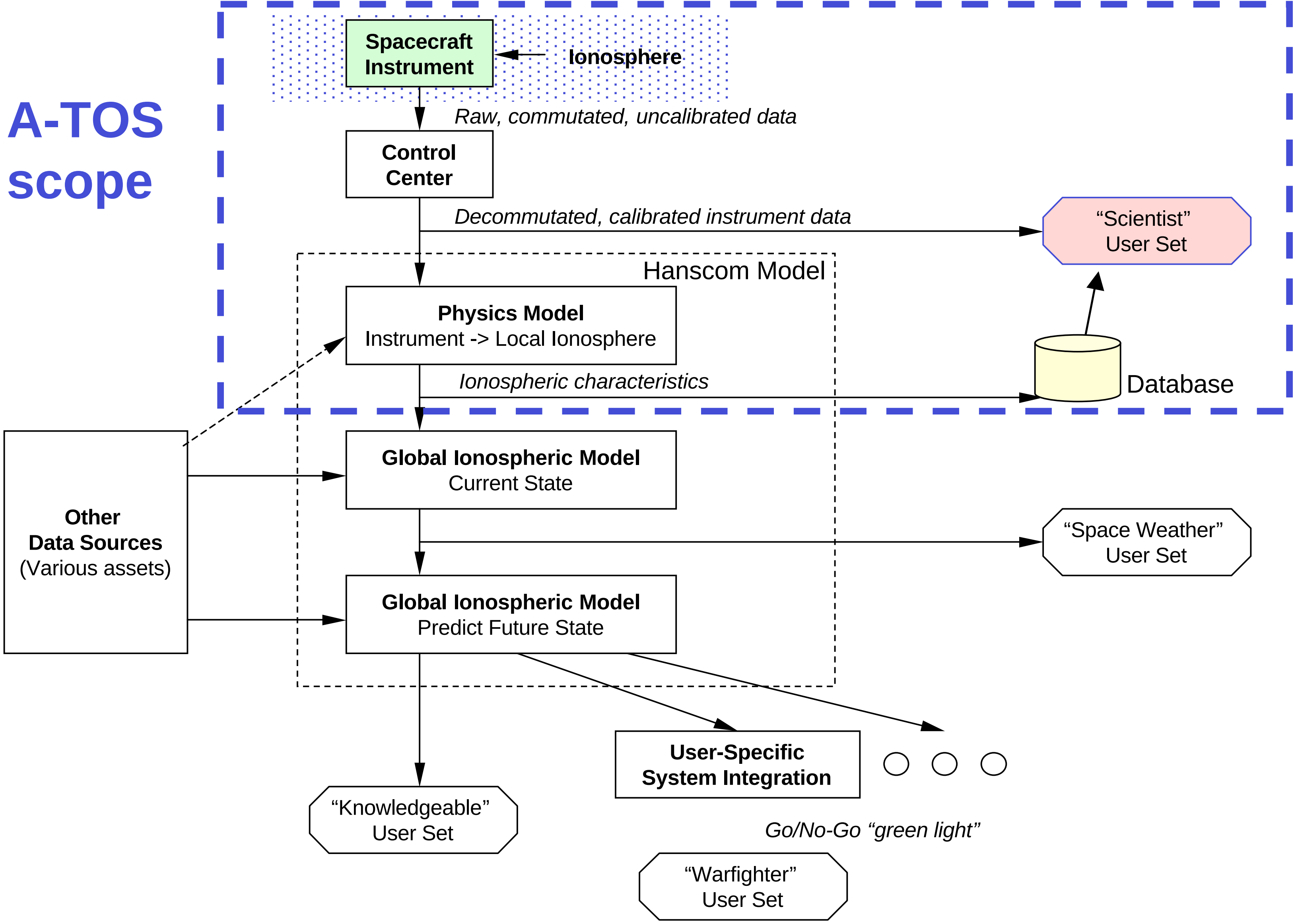
Scoping



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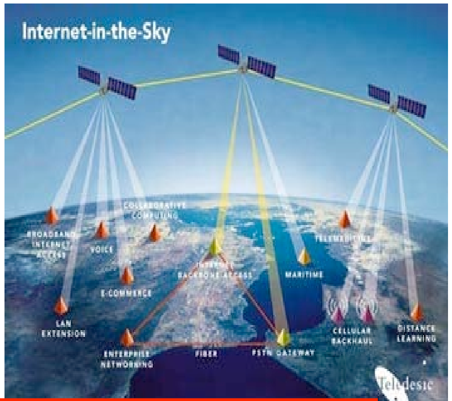
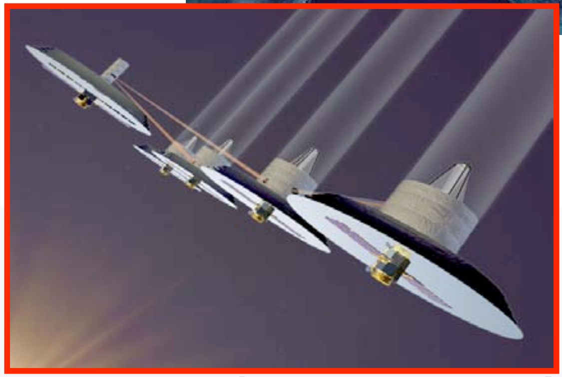
Attributes

- “what the decision makers need to consider”
- (and/or what the user truly cares about)
- Examples: Billable minutes = GINA metrics

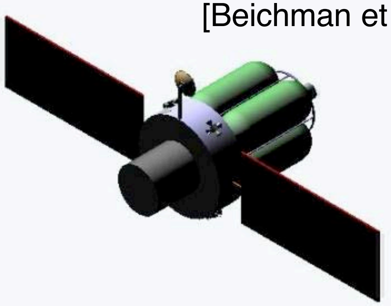
- TPF Pictures = camera performance metrics

- Rescue/move satellites = mass moving, grappling capability, timeliness
  - Could have sub-cartoons for above





[Beichman et al, 1999]

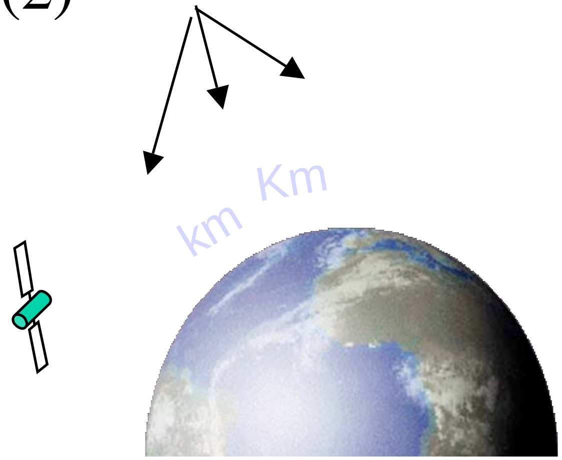


XTOS Attributes

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

(1)

(2)



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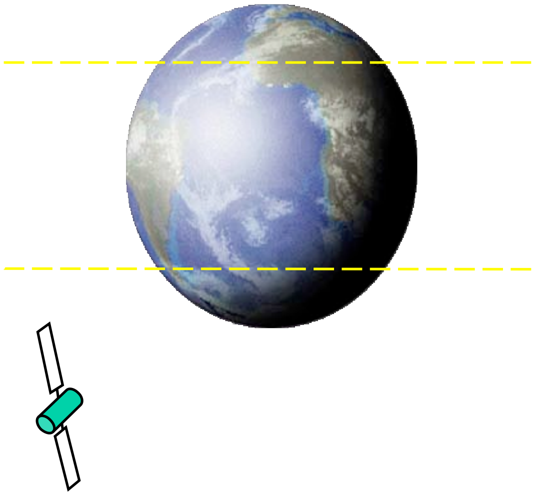

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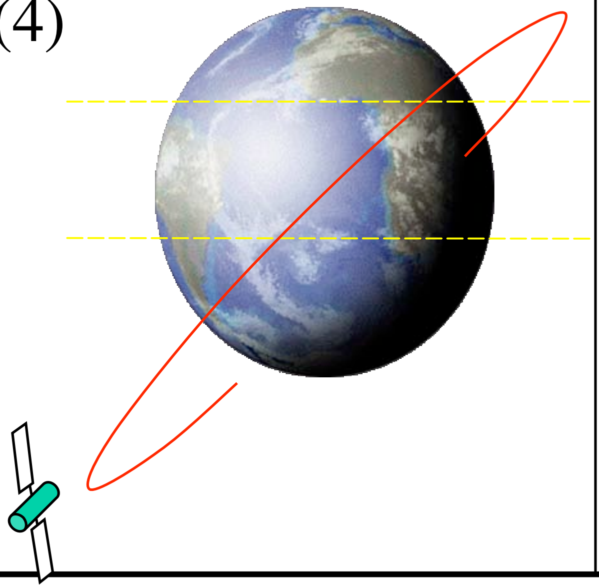

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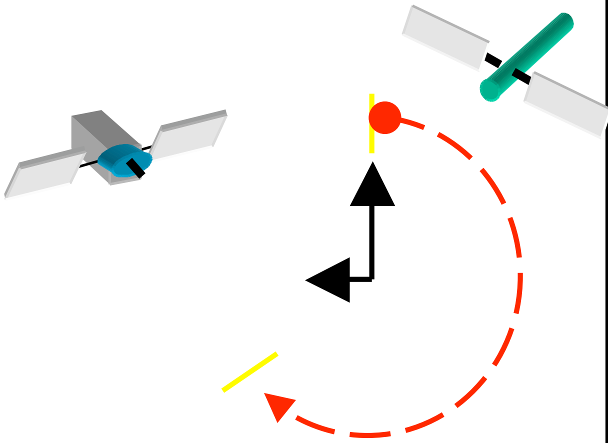
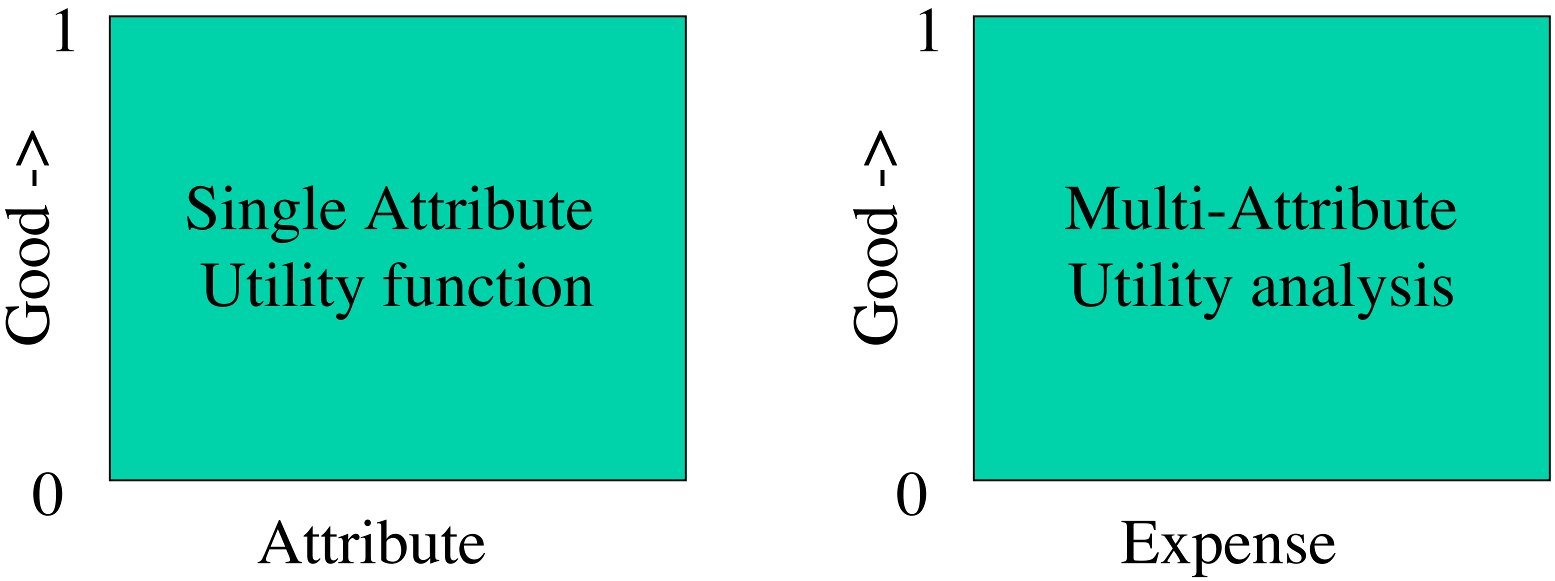
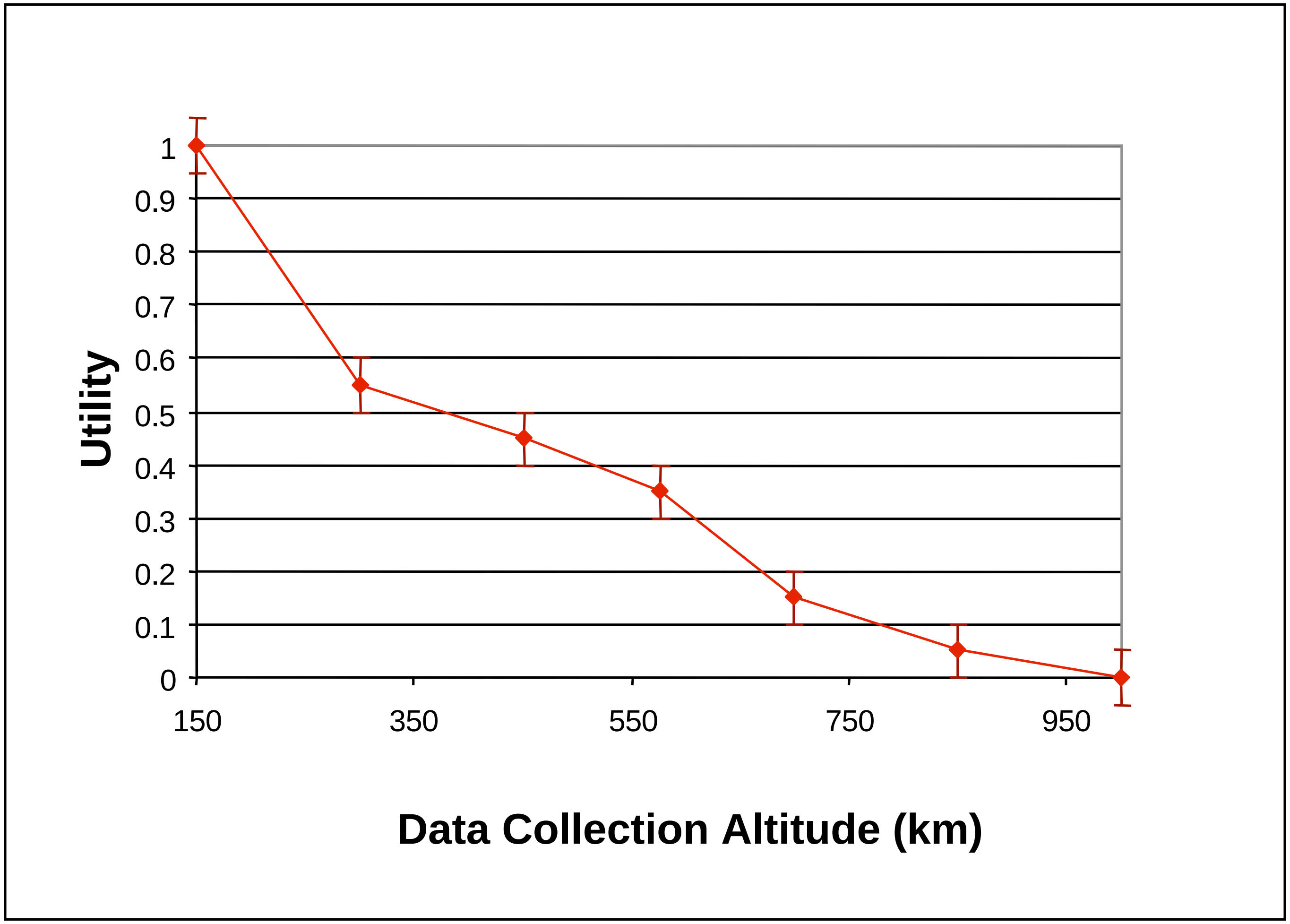


Utilities

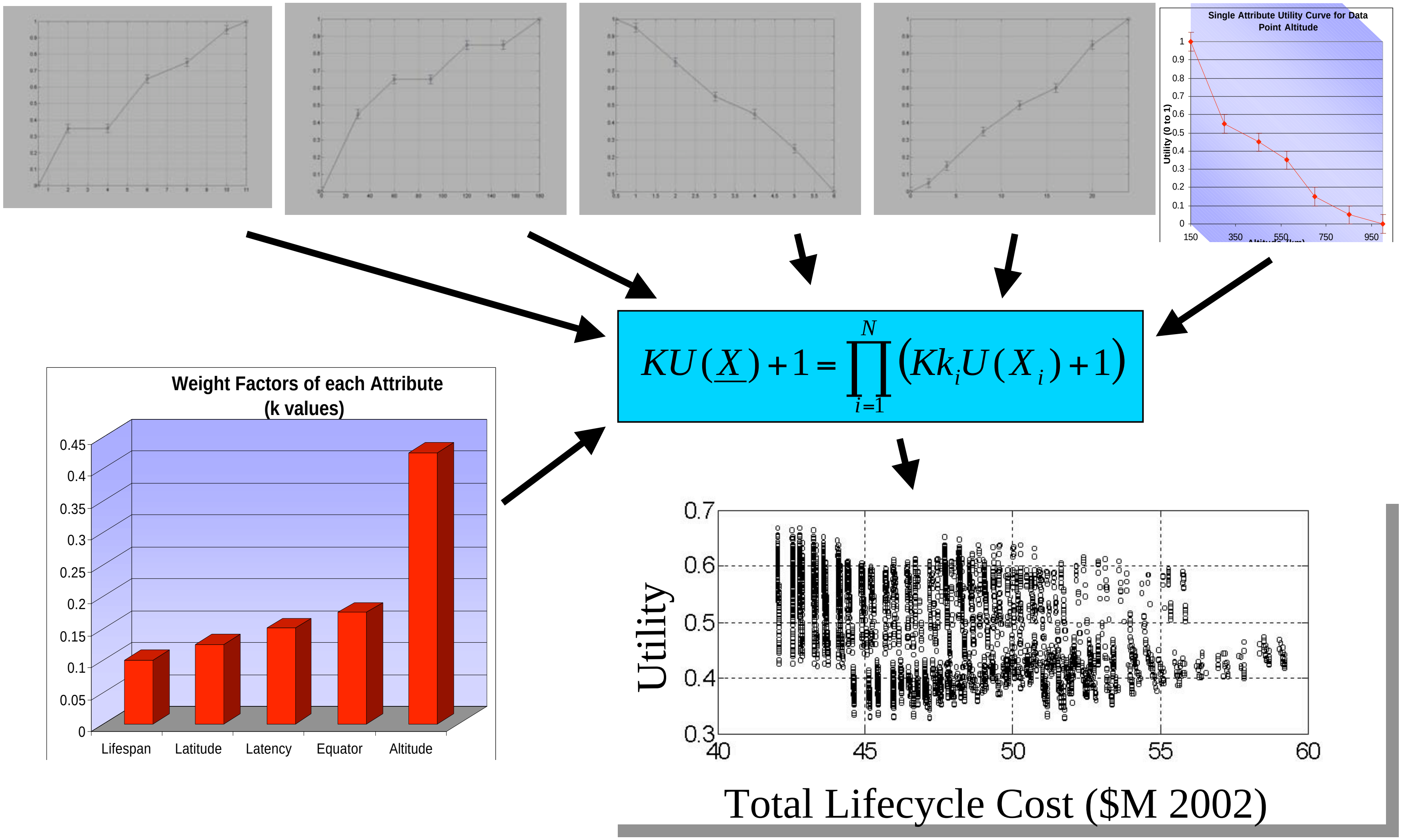
- “What the attributes are WORTH to the decision makers”
- Single Attribute utility maps attribute to utility
- Multi-attribute utility maps an architecture (as expressed by its attributes) to utility



Single Attribute Utilities



Multi-Attribute Utility



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

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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

Scoping-QFDs

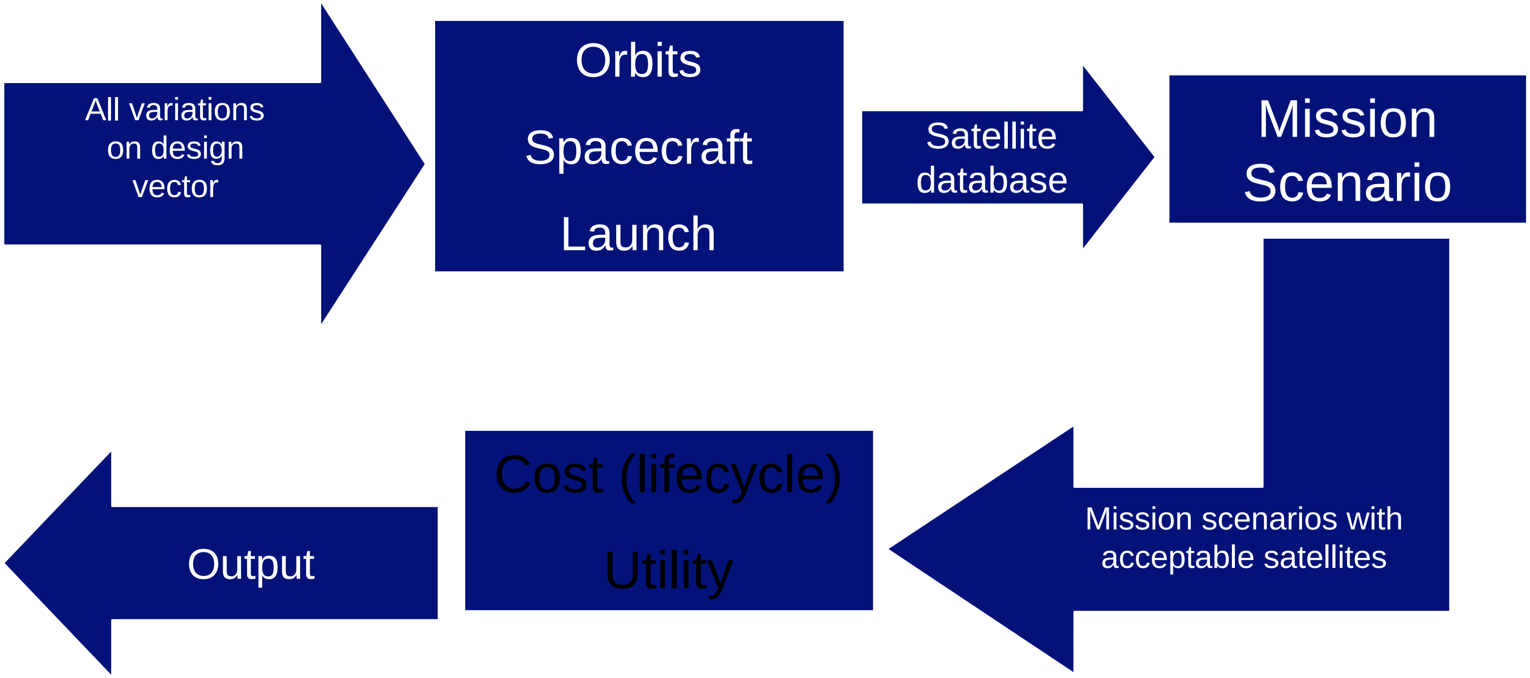
Attributes \ Design Vars	Perigee	Apogee	Delta-V	Propulsion	Inclination	Comm System	Ant. Gain	Power system	Mission Scenario	Total Impact
Data Lifespan	9	9	9	6	0	0	0	6	9	48
Sample Altitude	9	9	0	0	0	0	0	0	9	27
Diversity of Latitudes	0	0	0	0	9	0	0	0	9	18
Time at Equator	0	6	0	0	9	0	0	0	9	24
Latency	3	3	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

Mapping Design Vector to Attributes and Utilities - Simulation Models

XTOS Simulation Software Flow Chart



All variations on design vector

Orbits

Spacecraft

Launch

Satellite database

Mission Scenario

Mission scenarios with acceptable satellites

Cost (lifecycle)

Utility

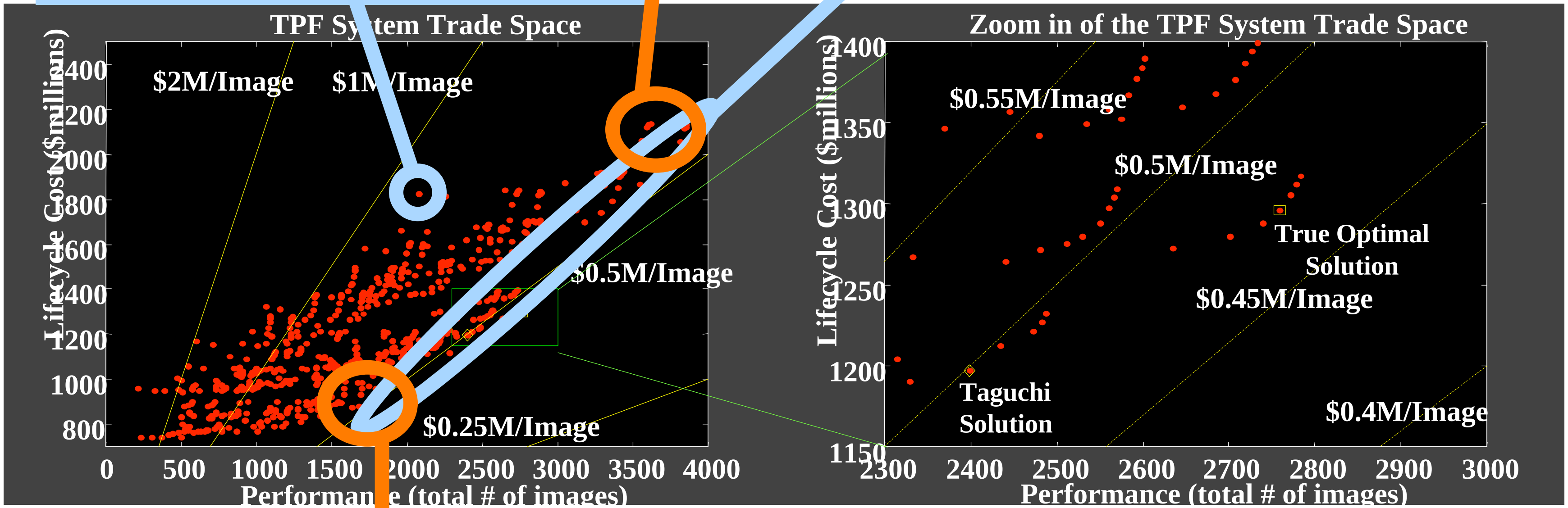
Output

Exploring the Tradespace

Cadillac

Each point is an evaluated architecture

Many good architectures at c. $0.5M/Image

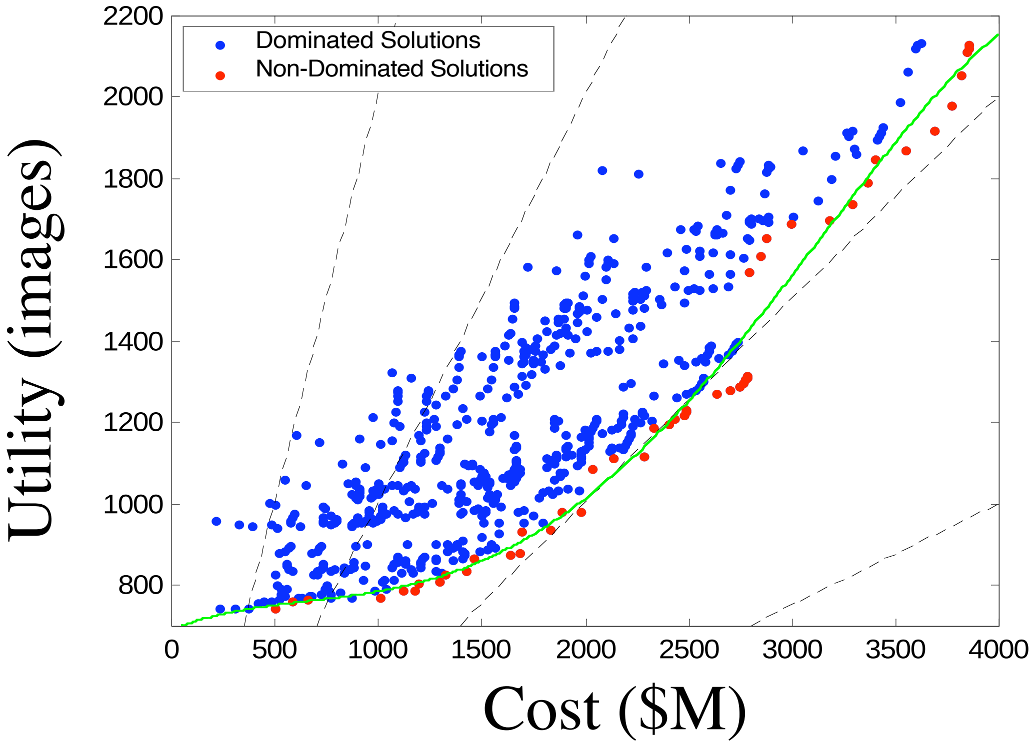


Chevy

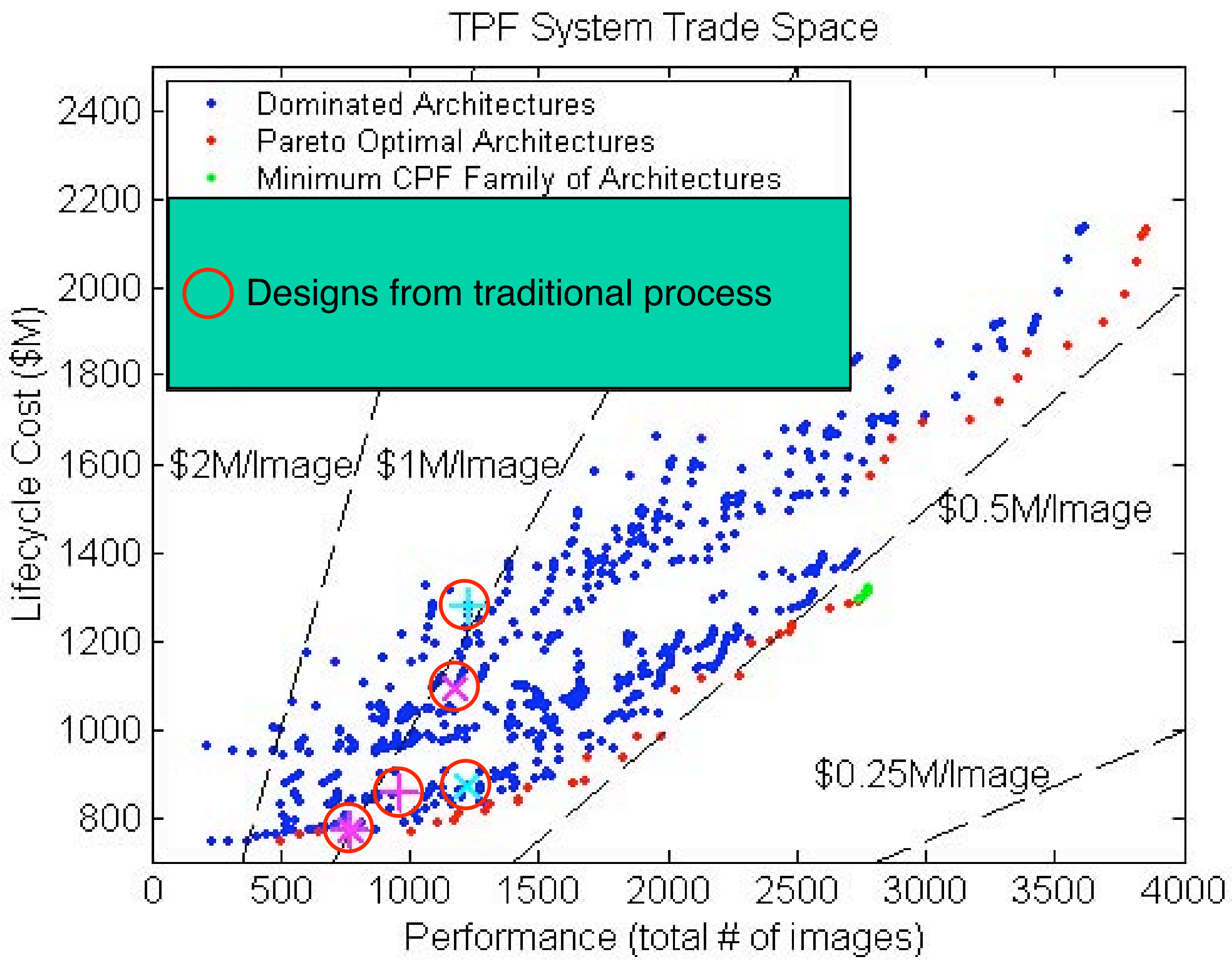
TPF: a science imaging system

The Pareto Front

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



Using the Trade Space to Evaluate Point Designs

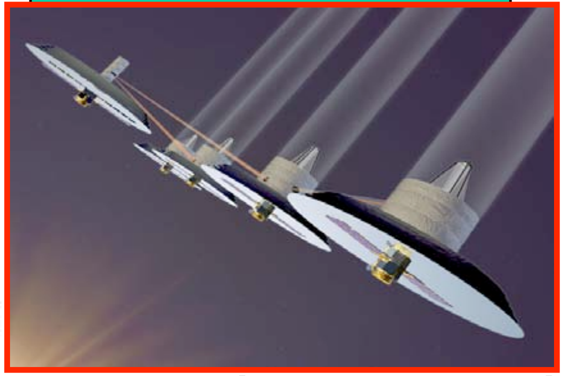


○ Designs from traditional process

From Jilla, 2002

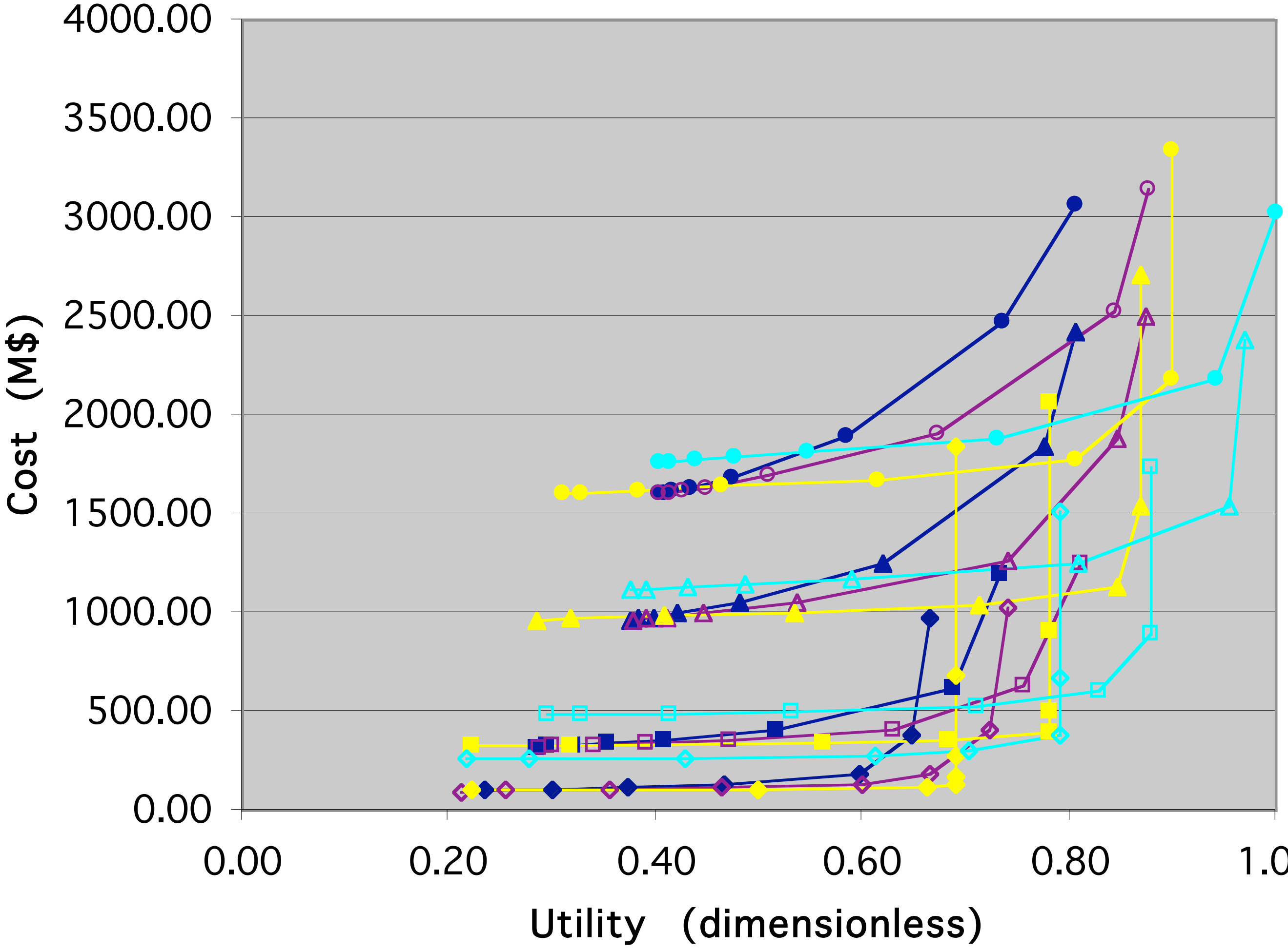
TPF

- 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]

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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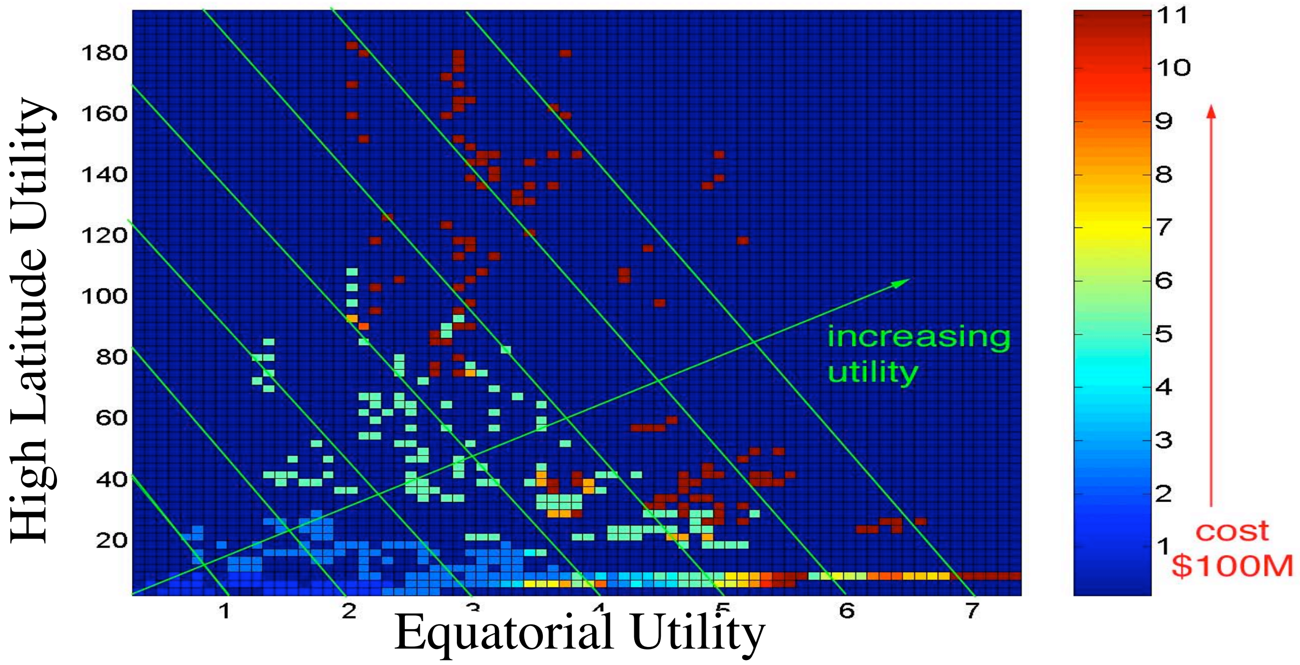
Questioning User Desires

- 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?

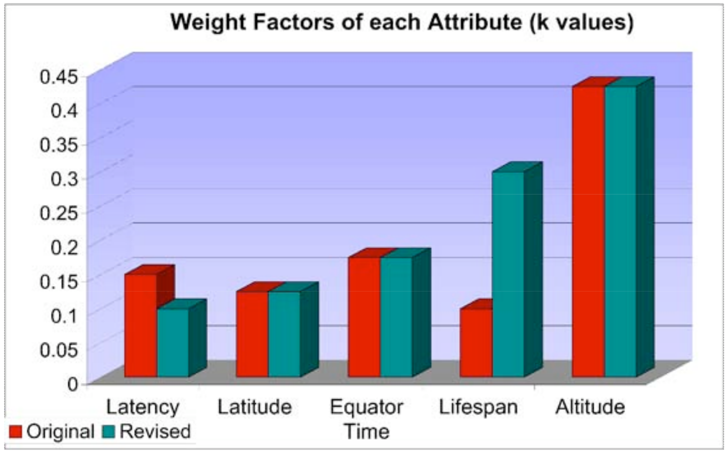
A-TOS

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

Color scale: Life Cycle Cost, 1380 data points, grid: 75x75, density: 0.08



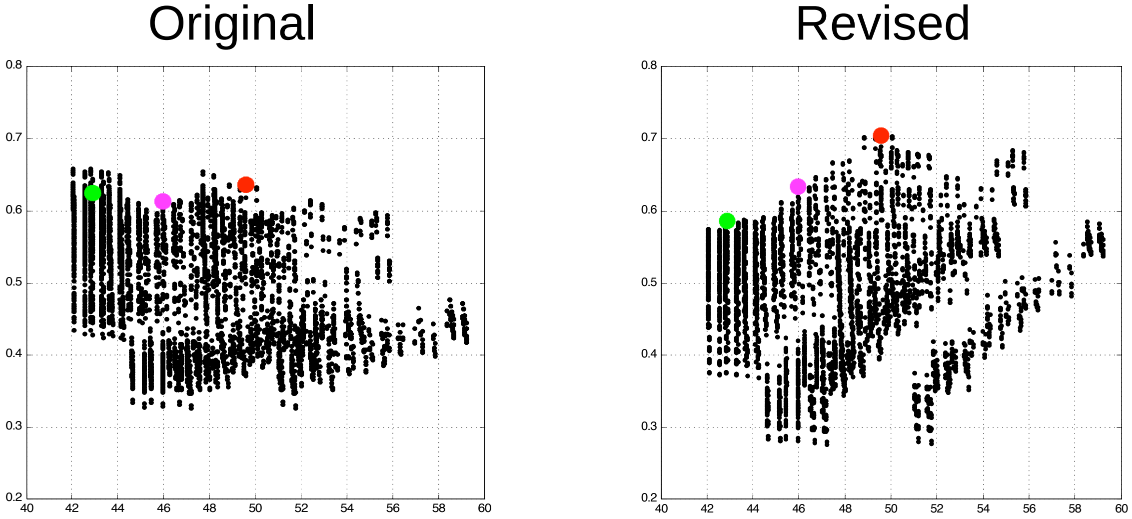
Changes in User Preferences Can be Quickly Understood



Architecture trade space reevaluated in less than one hour

User changed preference weighting for lifespan

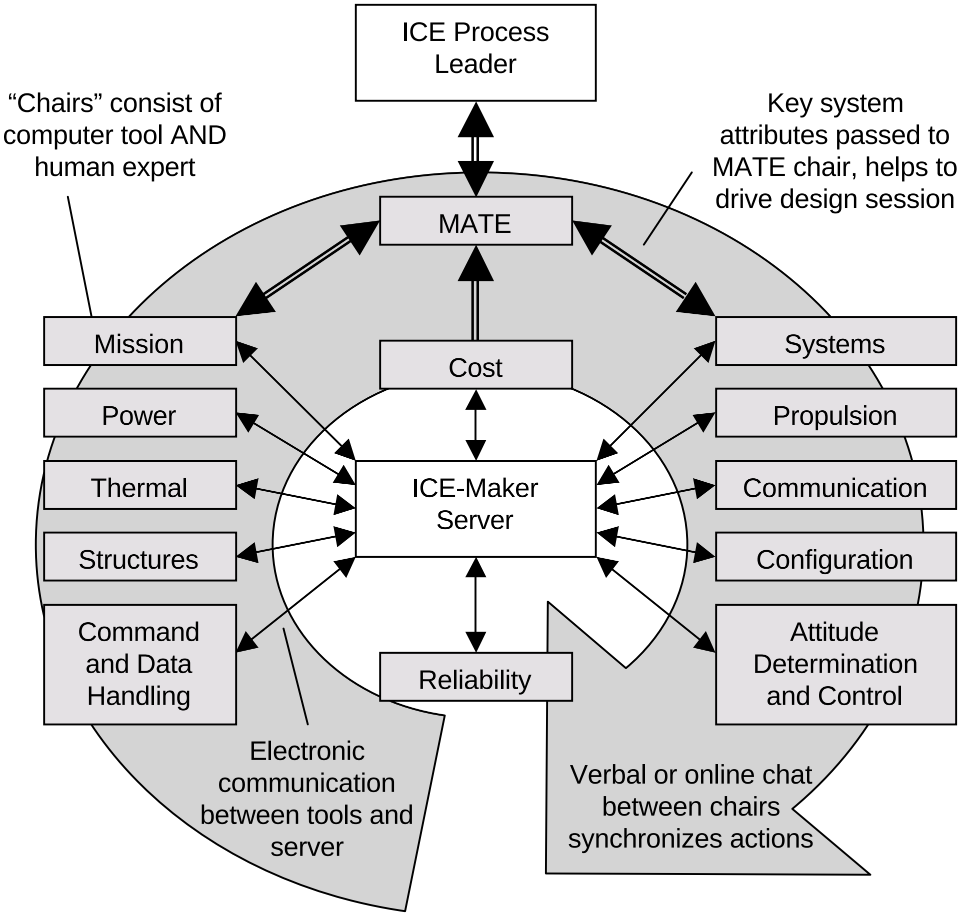
X-TOS



Integrated Concurrent Engineering (ICE)

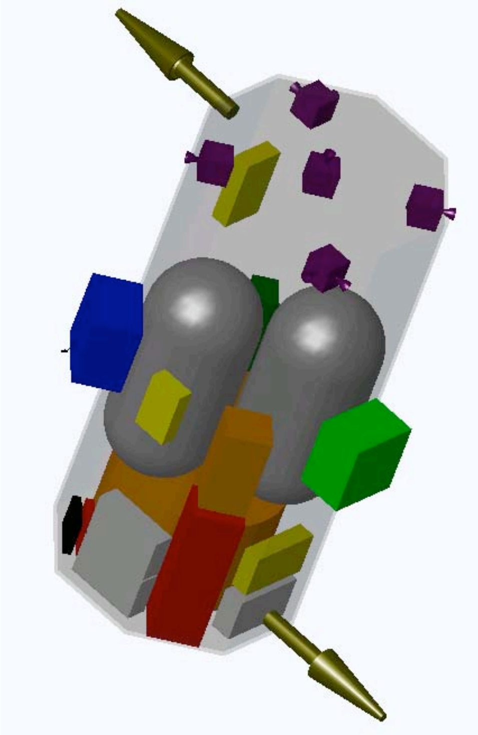
- ICE techniques from Caltech and JPL
- Linked analytical tools with human experts in the loop
- Very rapid design iterations
- Result is conceptual design at more detailed level than seen in architecture studies
- Allows understanding and exploration of design alternatives
- A reality check on the architecture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

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

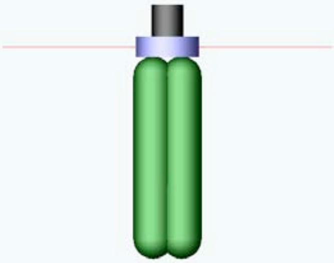
ICE Result - XTOS Vehicle



- 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

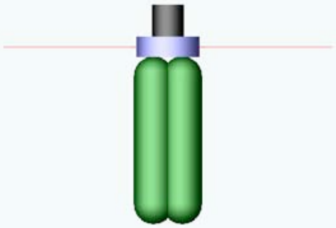
SPACETUG Tug Family (designed in a day)

Bipropellant



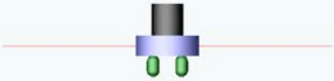
Wet Mass: 11689 kg

Cryogenic



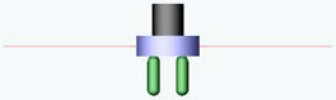
Wet Mass: 6238 kg

Electric – One way



Wet Mass: 997 kg

Electric – Return Trip



Wet Mass: 1112 kg

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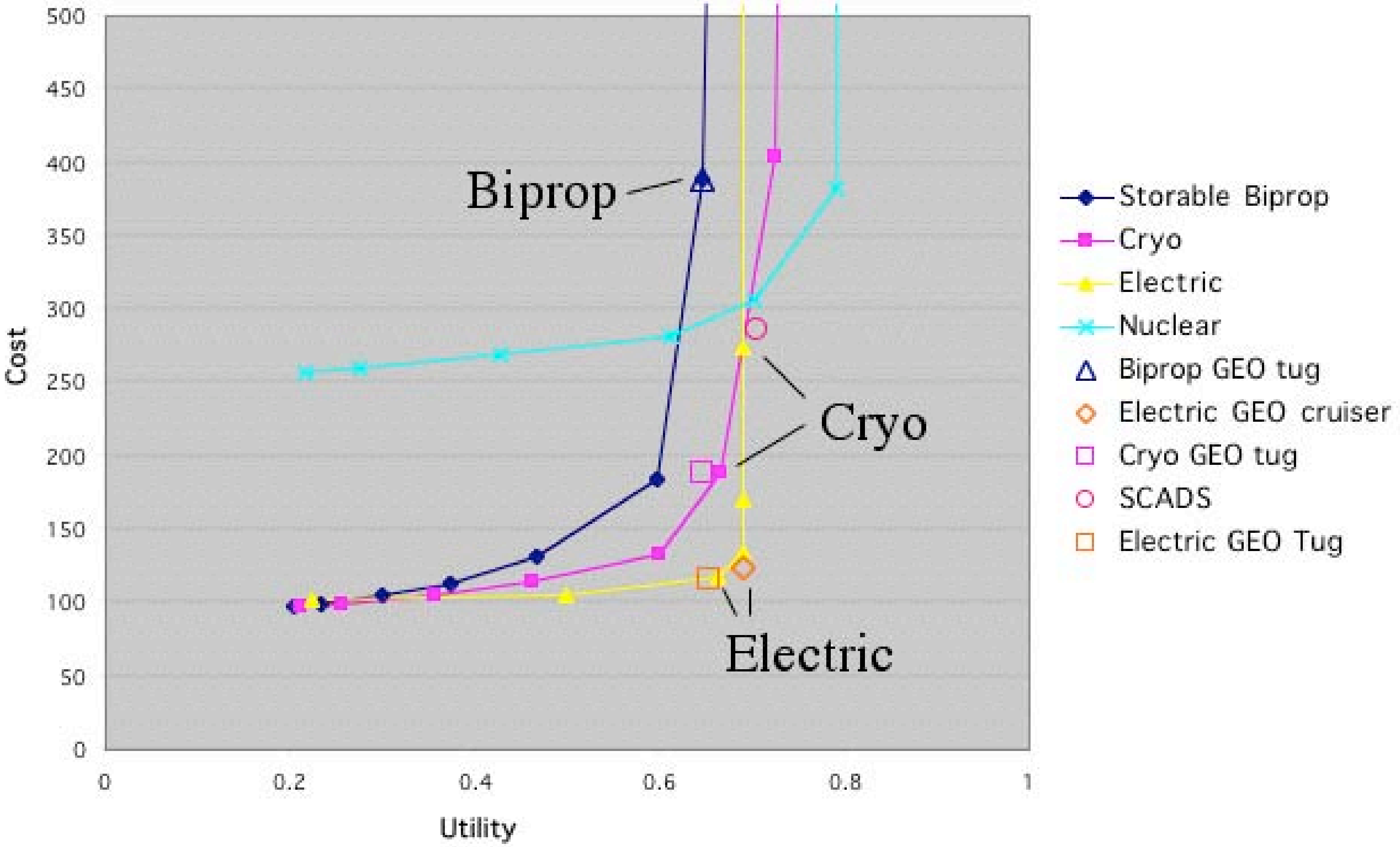
Trade Space Check



The GEO mission is near the “wall” for conventional propulsion

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*