Space Systems Policy Architecture Research Consortium (SSPARC)

MIT, Caltech, Stanford, NWC Sponsored by the NRO

Flexible Concept Formulation:

Architecture Research Employing Multi-Attribute Utility Analysis

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New Design Paradigms Workshop, JPL

Tuesday, June 26, 2001

Presentation Outline

- SSPARC
- Process Development
- Architecture Study Results
- Complete Design Support
- Future Plans

SSPARC Purpose and Organization

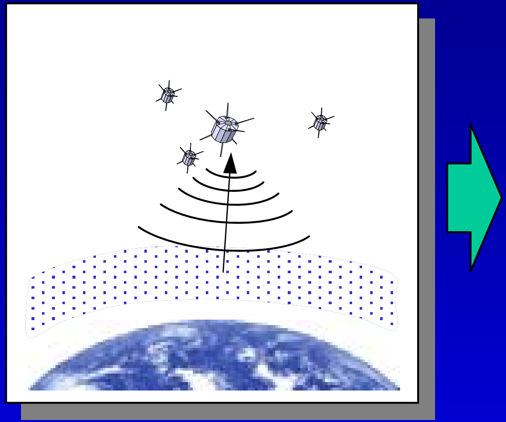
- **Problem: Current space system design practices result in high costs and long development times.**
- **MIT, Stanford, Caltech & the Naval War College have initiated a Center of Excellence in Space System, Policy, & Architecture sponsored by the NRO.**
- **Question: Can new paradigms be created to give designs and capabilities that are rapid, inexpensive & flexible?**
- **Three-pronged Approach**
  - **Develop, implement, demonstrate, and improve *process***
  - **Develop and improve *tool*s**
  - **Develop for the customer a needed *produc*t**

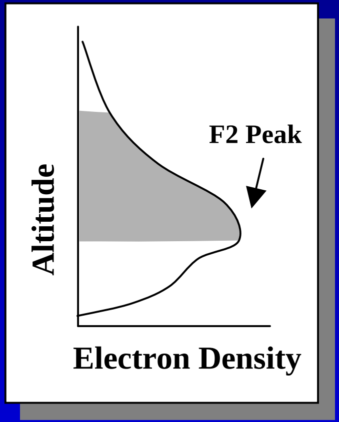
SSPARC Research Methods

- Developing tools and processes with application to NRO product
- Product: Terrestrial Observer Swarm (TOS)
  - A-TOS: Preliminary in situ mission
  - B-TOS: Architecture Study
  - C-TOS: Spacecraft Design
- Product Motivation:
  - Ionosphere disturbs propagation of EM waves
  - Characterize Ionosphere using a topside sounder for AFRL model, which uses Vertical Total Electron Content (TEC), Electron Density Profile (EDP), Beacon Angle of Arrival (AOA)
  - Payload B: NRO Black Box

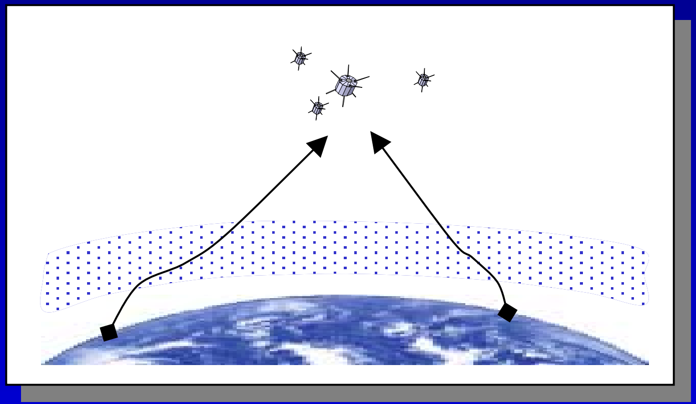
B-TOS Payload Mission Overview

Electron Density Profile (EDP)

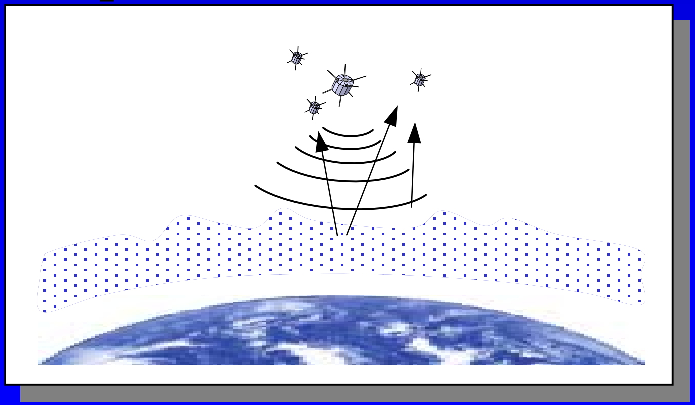




Beacon Angle of Arrival (AOA)

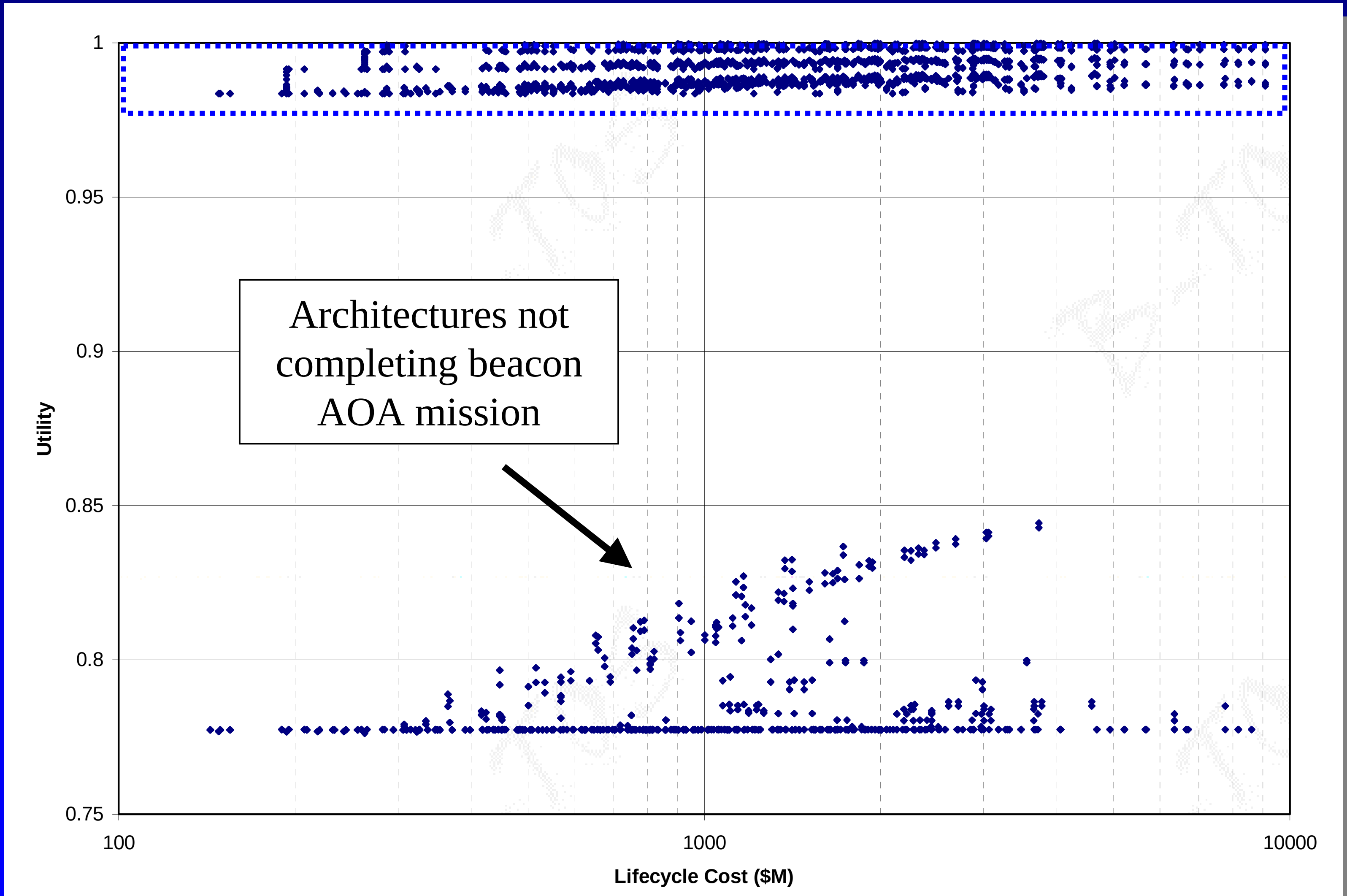


Ionosphere Turbulence



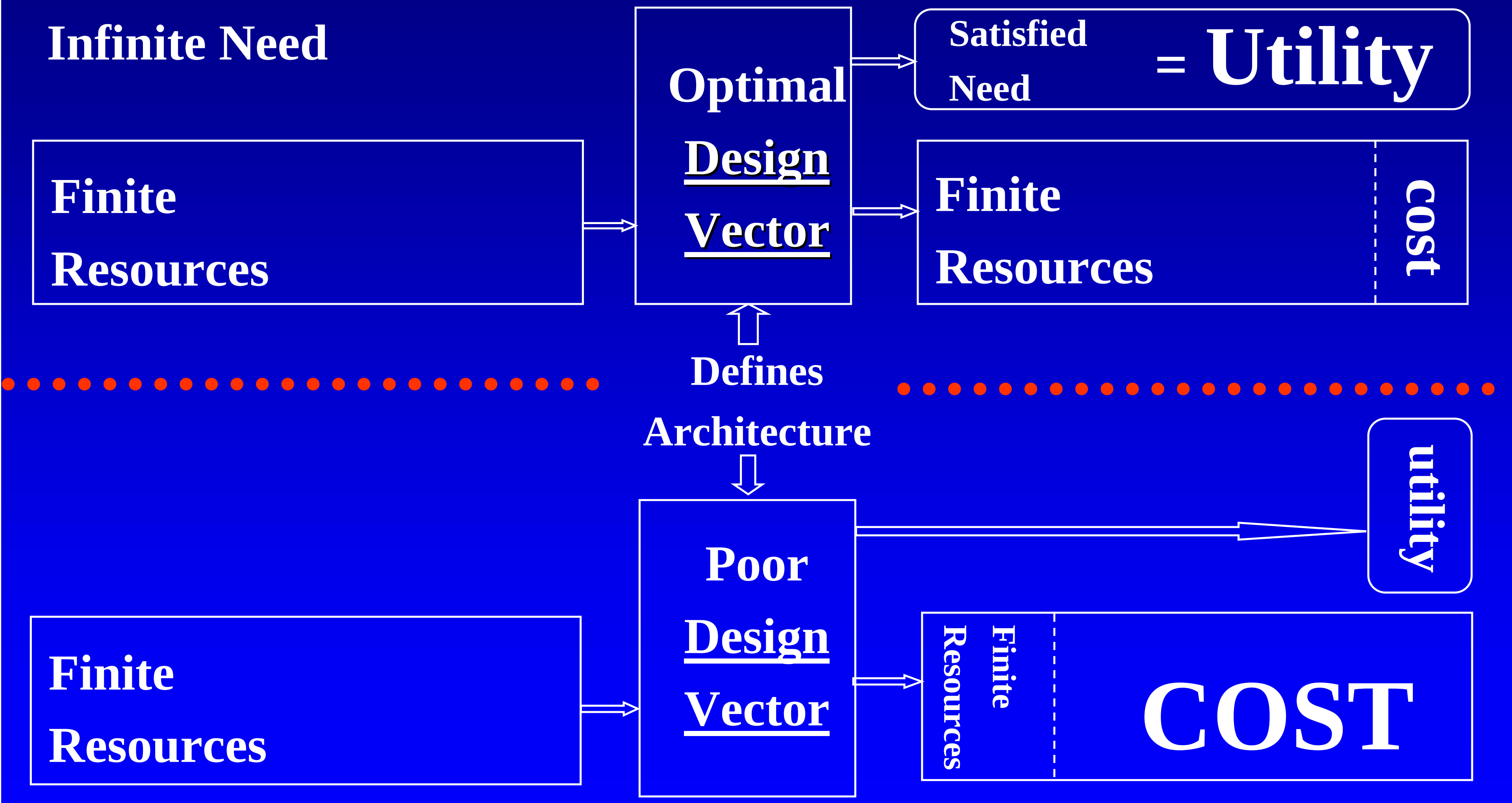
Payload "B"

Lifecycle Costs vs. Utility
(Entire Tradespace: 4,033 Architectures)

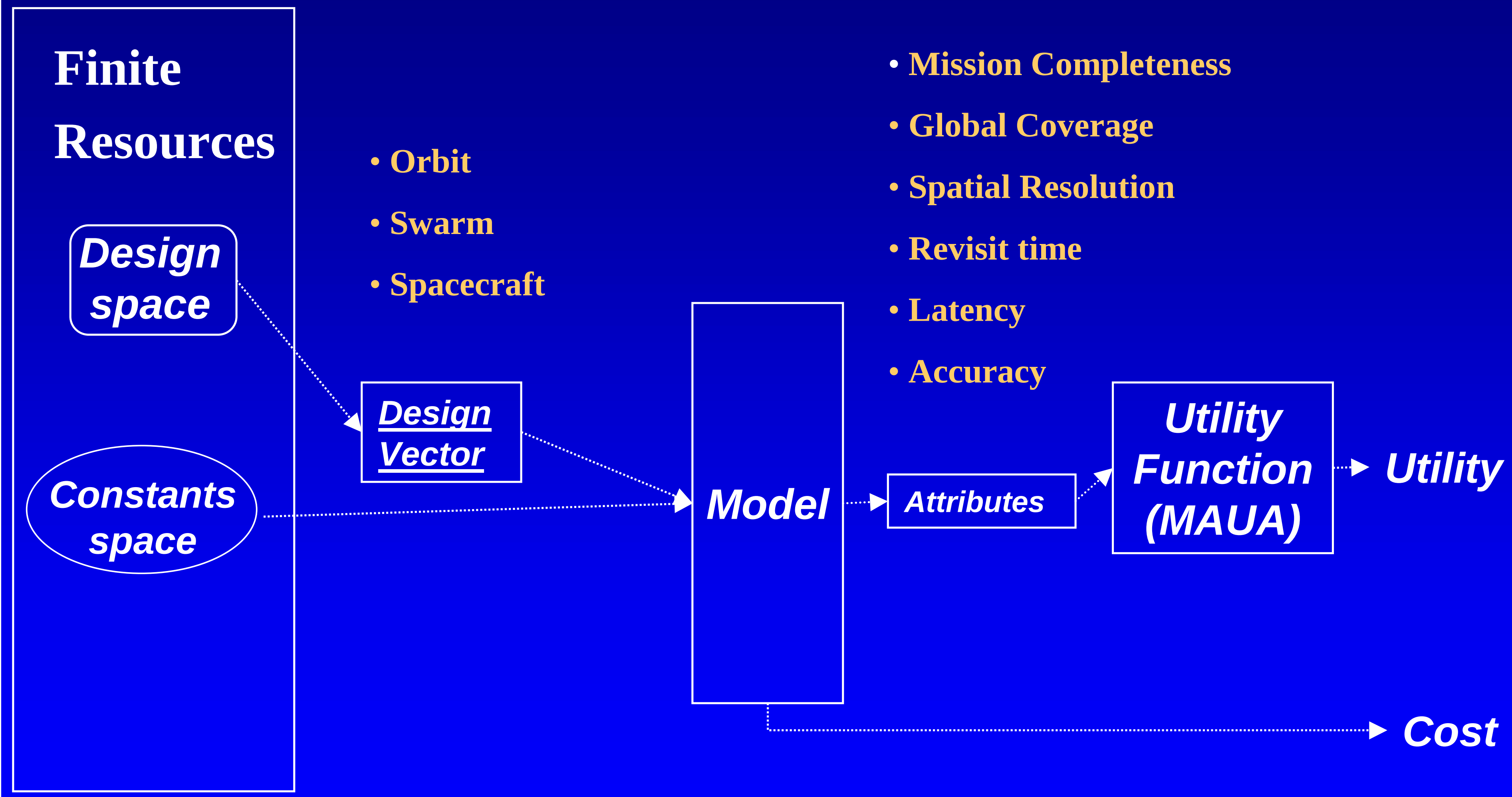


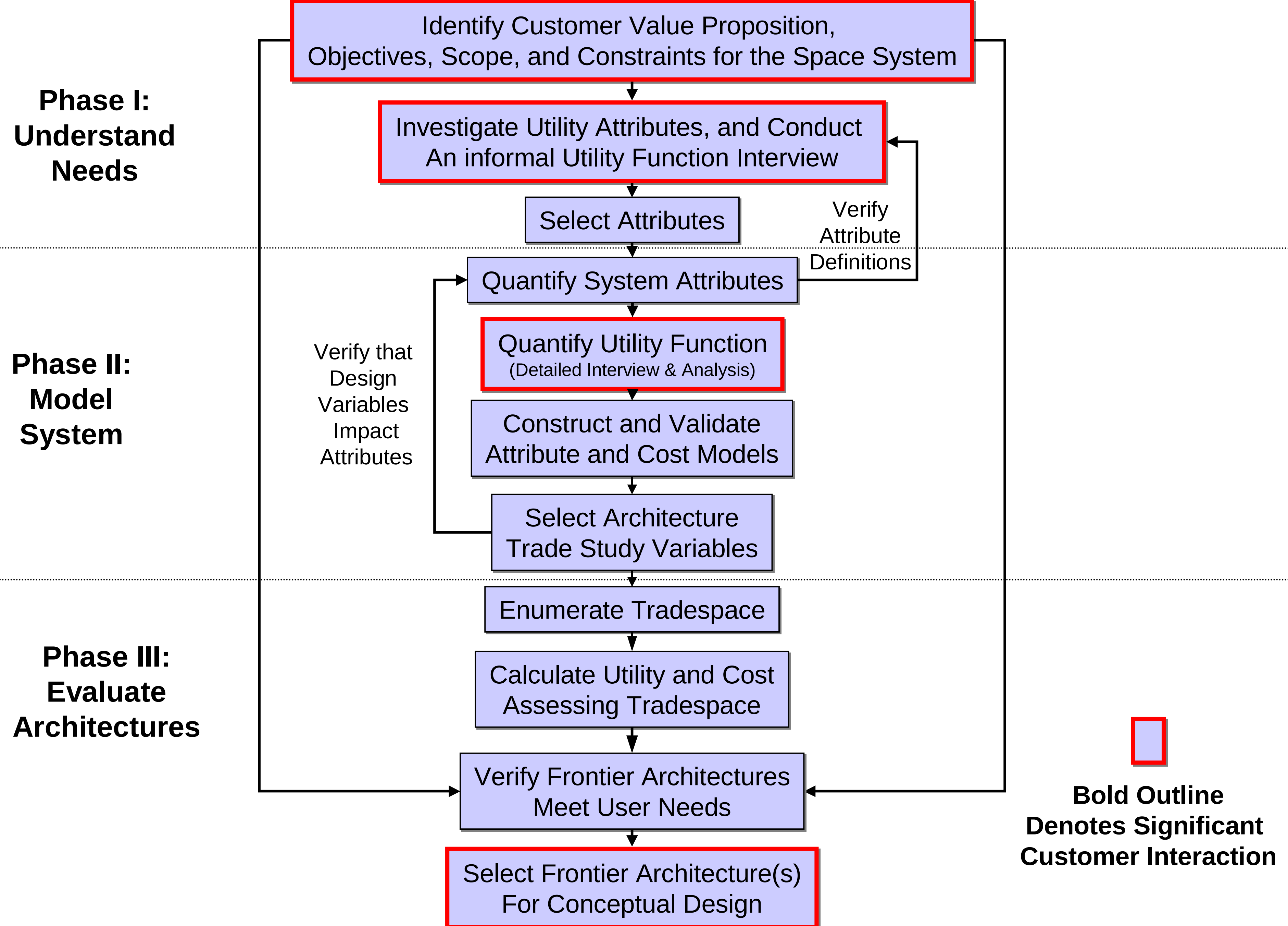
Completing AOA mission is main driver for utility

Product Development & Evaluation



Product Development & Evaluation




Phase I: Understand Needs
Phase II: Model System
Phase III: Evaluate Architectures
Identify Customer Value Proposition, Objectives, Scope, and Constraints for the Space System
Investigate Utility Attributes, and Conduct An informal Utility Function Interview
Select Attributes
Verify Attribute Definitions
Quantify System Attributes
Verify that Design Variables Impact Attributes
Quantify Utility Function
(Detailed Interview & Analysis)
Construct and Validate Attribute and Cost Models
Select Architecture Trade Study Variables
Enumerate Tradespace
Calculate Utility and Cost Assessing Tradespace
Verify Frontier Architectures Meet User Needs
Select Frontier Architecture(s) For Conceptual Design
Bold Outline Denotes Significant Customer Interaction

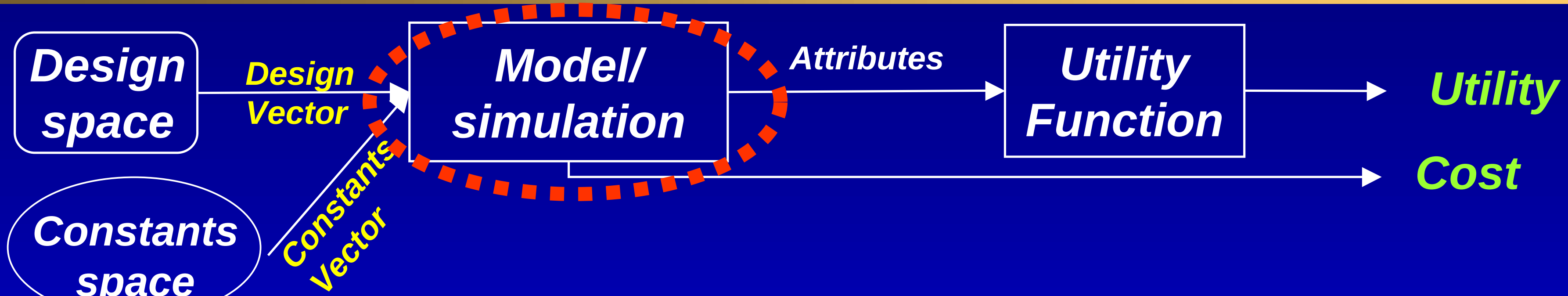
Design Vector Variables

• Circular orbit altitude (km)	1100, 1300
• Number of Planes	1, 2, 3, 4, 5
• Number of Swarms/Plane	1, 2, 3, 4, 5
• Number of Satellites/Swarm	4, 7, 10, 13
• Radius of Swarm (km)	0.18, 1.5, 8.75, 50
• 5 Configuration Studies	Trades payload, communication, and processing capability

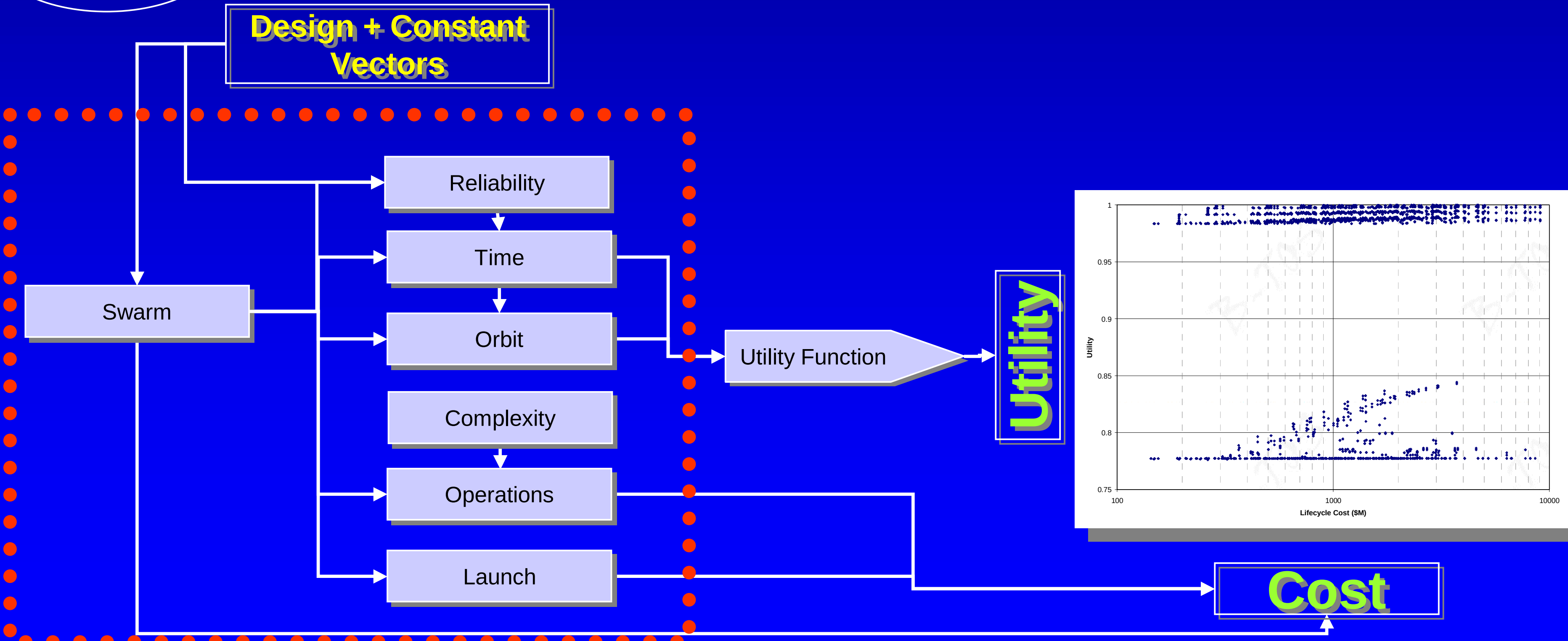
4,033 Architectures

73 Hrs total computation time with 8 Pentium IIIs

Modeling



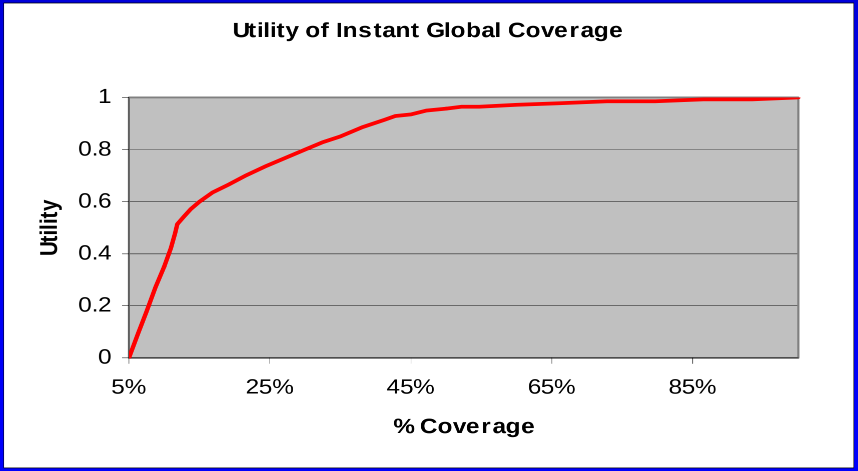
Design space
Design Vector
Constants space
Constants Vector
Model/ simulation
Attributes
Utility Function
Utility
Cost



Design + Constant Vectors
Swarm
Reliability
Time
Orbit
Complexity
Operations
Launch
Utility Function
Utility
Cost
1
0.95
0.9
0.85
0.8
0.75
Utility
100
1000
10000
Lifecycle Cost ($M)

Attributes to Utility:MAUA Results

1. **Mission Completeness:** Sub-set of missions performed
2. **Spatial Resolution:** Arc length of Earth between measurements
3. **Revisit Time:** Time between subsequent measurements of the same point above the Earth
4. **Latency:** Time delay from measurement to end user
5. **Accuracy:** Measurement error in angle of arrival data
6. **Instantaneous Global Coverage:** % of Earth's surface in view



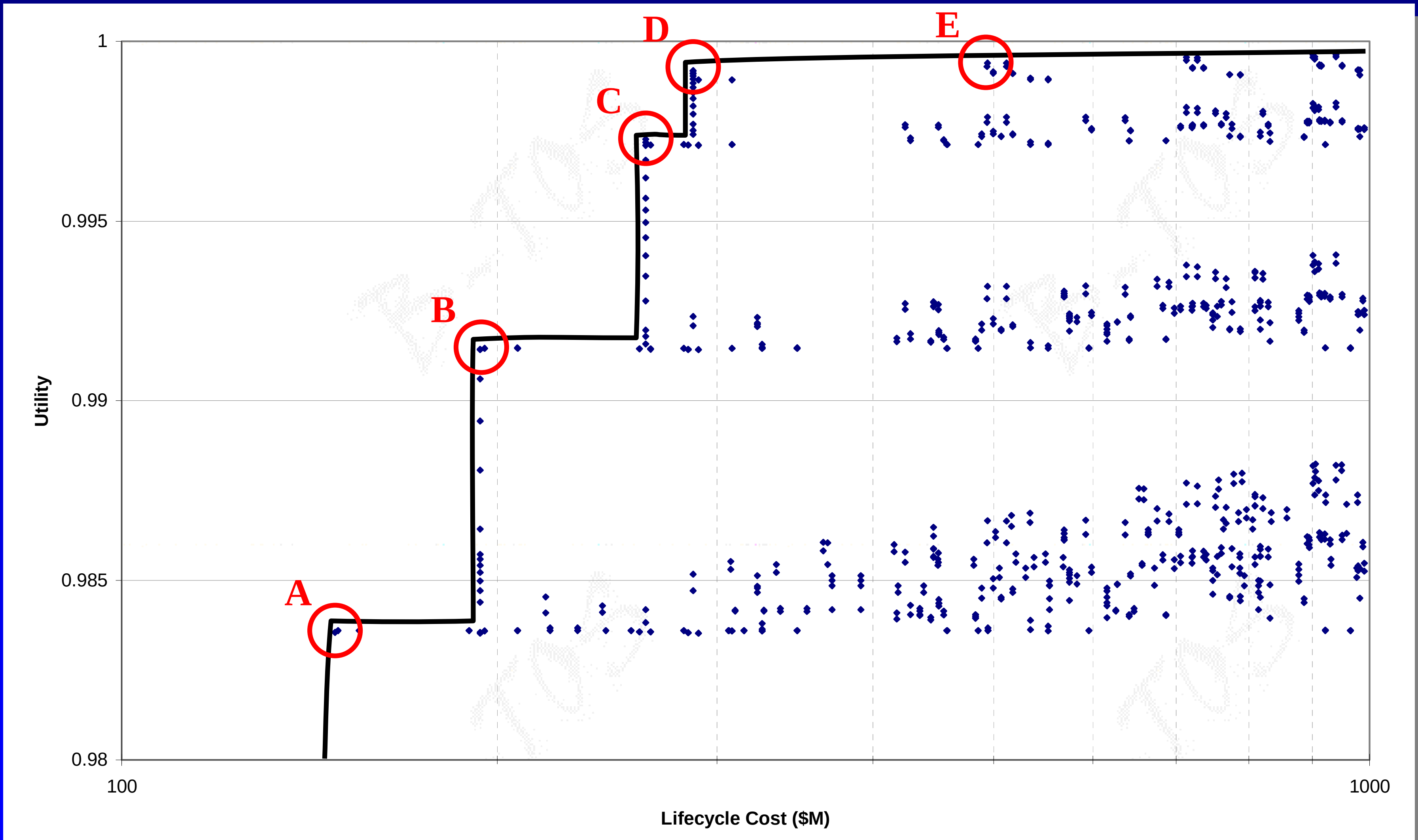
- Attributes define desired system performance
- Utility is a numeric value for performance preferences

Model Analytical Capability

- Variation of orbital geometries
- Multiple swarm size and density options
- Satellites have individually varying functionality
- Evaluated more than 4,000 Architectures

Model currently produces a focused tradespace, not a single-point architecture—**key to flexibility**

Lifecycle Costs vs. Utility
(Frontier Architectures)

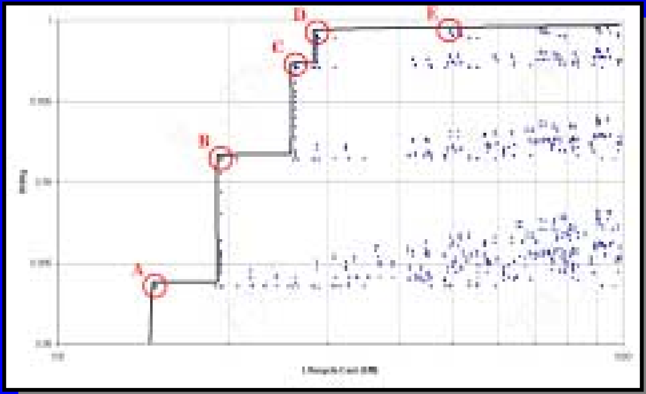


Frontier architectures are the most desirable

Frontier Architecture Design Vectors

Point	A	B	C	D	E
Altitude (km)	<-- 1100 -->				
Num of Planes	<-- 1 -->				
Swarms/Plane	1	1	1	1	2
Satellites/Swarm	4	7	10	13	13
Swarm Radius (km)	0.18	1.5	8.75	50	50
Functionality Study	<-- #5 -->				

Recall:



Study	5	
Type	M	D
Number	1	3+
Payload (Tx)	Yes	No
Payload (Rx)	Yes	Yes
Processing	Yes	No
TDRSS Link	Yes	No
Intra-Swarm Link	Yes	Yes

Frontier Attributes, Utility, & Cost

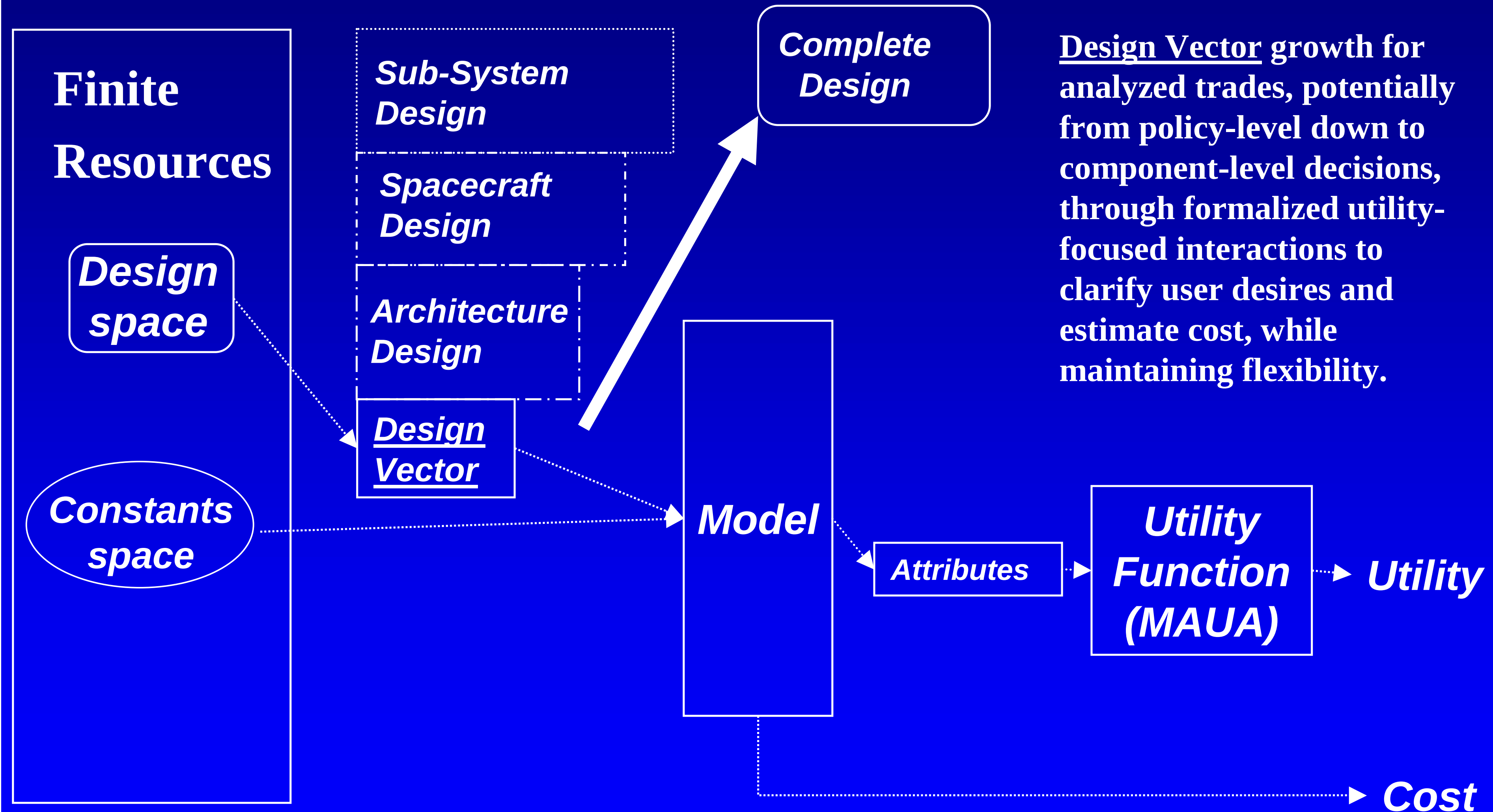
Point	A	B	C	D	E
Spatial Resolution (deg)	4.36	5.25	7.34	9.44	9.44
Revisit Time (min)	805	708	508	352	195
Latency (min)	3.40	3.69	4.36	5.04	5.04
Accuracy (deg)	0.15	0.018	0.0031	0.00054	0.00054
Inst. Global Coverage	0.29%	0.29%	1.15%	2.28%	4.55%
Utility	0.9835	0.9914	0.9973	0.9992	0.9994
IOC Cost ($M)	90	119	174	191	347
Lifecycle Cost ($M)	148	194	263	287	494

Frontier architectures can be evaluated using attributes in place of non-dimensional utility values

Complete Design Support

- Process started with MIT Space Systems Lab
- Refined Spring of 2001 at MIT SSPARC
- C-TOS spacecraft design project, summer 2001
  - Starting with B-TOS results design mother / daughter ships
  - Using Integrated Concurrent Engineering (ICE)
  - Distributed team at MIT, Caltech, and Stanford
  - Brief design to NRO 23 August 2001
- From architecture study wrote “requirements” for spacecraft
- Systematic means of moving from policy-level detail to hardware-level detail
- Systematic means of clarifying user needs

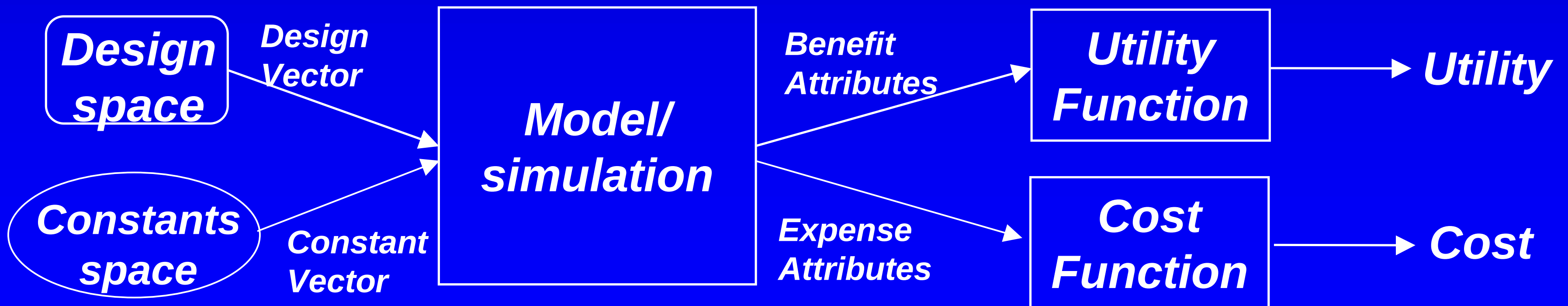
Complete Design Support



Design Vector growth for analyzed trades, potentially from policy-level down to component-level decisions, through formalized utility-focused interactions to clarify user desires and estimate cost, while maintaining flexibility.

Future Plans

- Detailed spacecraft design C-TOS
- Apply to case studies besides TOS missions
- Begin to see possible application for both more detailed design and for higher-level concept decisions
- Verify further and improve flexibility of MAUA
- Consider broader cost function



Backup Slides

B-TOS Design Vector Variables

Group	Variable	Rationale
Large Scale Arch.	Apogee Altitude	Specifies orbit/relationship to ionosphere
	Perigee Altitude	Specifies orbit/relationship to ionosphere
	Number of Planes	Key to meeting global coverage needs
	Swarm per Plane	Key to meeting global coverage needs
Swarm Arch.	Satellites per Swarm	Local coverage resolution
	Size of Swarm	Local coverage resolution
Vehicle Arch.	Number of Sounding Antennas	Captures functionality trade
	Sounding	Captures functionality trade
	Short Range Communications	Captures functionality trade
	Long Range Communications	Captures functionality trade
	On-Board Processing	Captures functionality trade

- **Payload, four choices available:**
  - **0 = none**
  - **1 = send**
  - **2 = receive**
  - **3 = both**
- **Communication and processing, two choices available:**
  - **0 = none**
  - **1 = yes (all)**

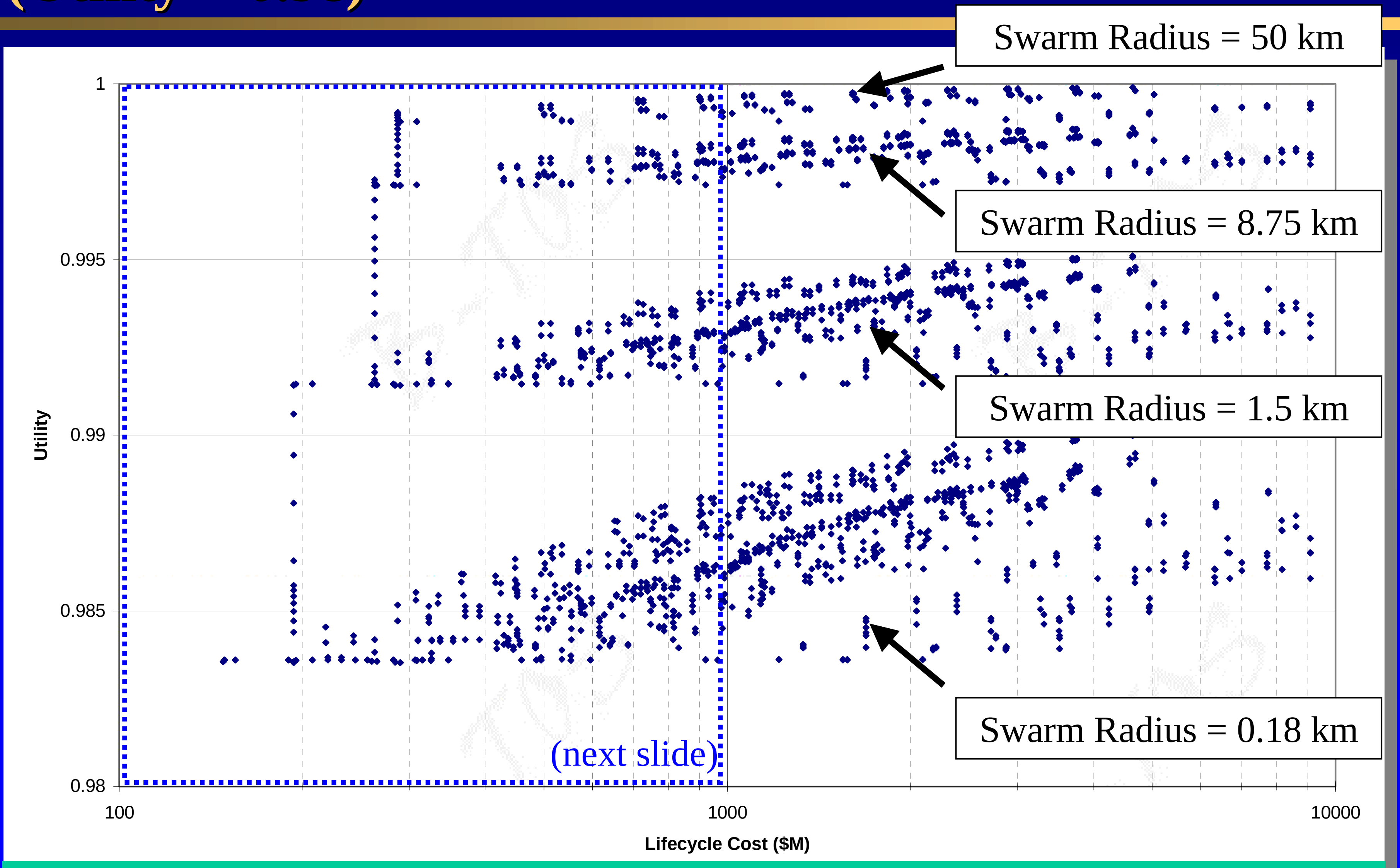
Configuration Studies

Study	1		2		3		4		5	
Type	M	D	M	D	M	D	M	D	M	D
Number	**4+**	**0**	1	3+	1	3+	1	3+	1	3+
Payload (Tx)	Yes	n/a	Yes	Yes	Yes	Yes	**No**	Yes	**Yes**	**No**
Payload (Rx)	Yes	n/a	Yes	Yes	Yes	Yes	**No**	Yes	**Yes**	Yes
Processing	Yes	n/a	Yes	**No**	Yes	**Yes**	Yes	No	Yes	No
TDRSS Link	Yes	n/a	Yes	**No**	Yes	No	Yes	No	Yes	No
Intra-Swarm Link	**No**	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

M = Mothership **D = Daughter**

- **Study 1: All spacecraft are independent**
- **Study 2: Mothership processes and downlinks**
- **Study 3: Distributed processing**
- **Study 4: Mothership dedicated to processing and downlink (no payload)**
- **Study 5: Mothership processes, downlinks, and has payload transmitter**

Lifecycle Costs vs. Utility
(Utility > 0.98)



Radius of the swarm is the main differentiator between architectures of high utility

Multi-Attribute Utility Function

$$KU(\underline{X})+1=\prod_{i=1}^{6}\left(Kk_iU(X_i)+1\right)$$

Normalization constant

Multi-attribute utility function

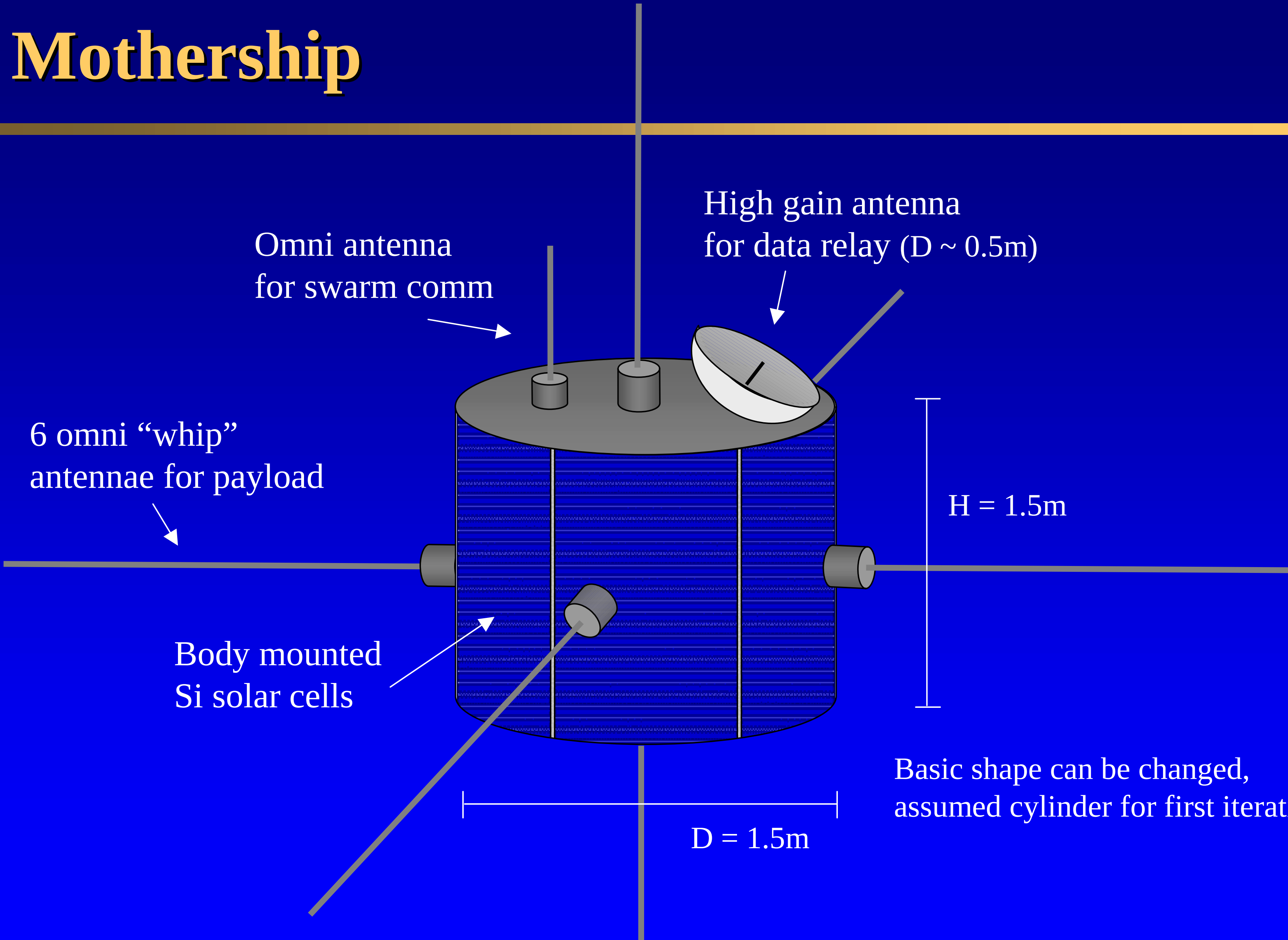
Relative “weight”

Single attribute utility

Subsystem Breakup and Descriptions

Sub-system	Requirement	Approach
Power	Full ops at end of life, peak and avg	Size battery and solar cell
Thermal	Acceptable temp range at eol, temp range	Energy balance
Payload	List from customer	Set requirements for other systems
Comm	Comm through TDRSS and with all daughters	Link budget
Attitude	Set by payload	Select and size sensors, wheels, and motors
Structure	Not fail or resonate	15% mass fraction budget
C.D.H	Support operations, survive environment	Recall ops scenarios, develop link budget inputs, select and size computers and recorders
Propulsion	Provide deltaV and max impulse to support ops scenarios	Select and size motors, possibly combined with attitude, consider drag, deorbit, margin, NOT differentials
Configuration	Fit in launch vehicle and config in 3D	Sketch or CAD
Mass	Launchable	Sum up systems' masses
Reliability	No single-point failures of vulnerable systems	Check batteries, computers, sensors, thrusters, thermal
Cost	Not exceed reasonable cost	SMAD cost estimating relationships

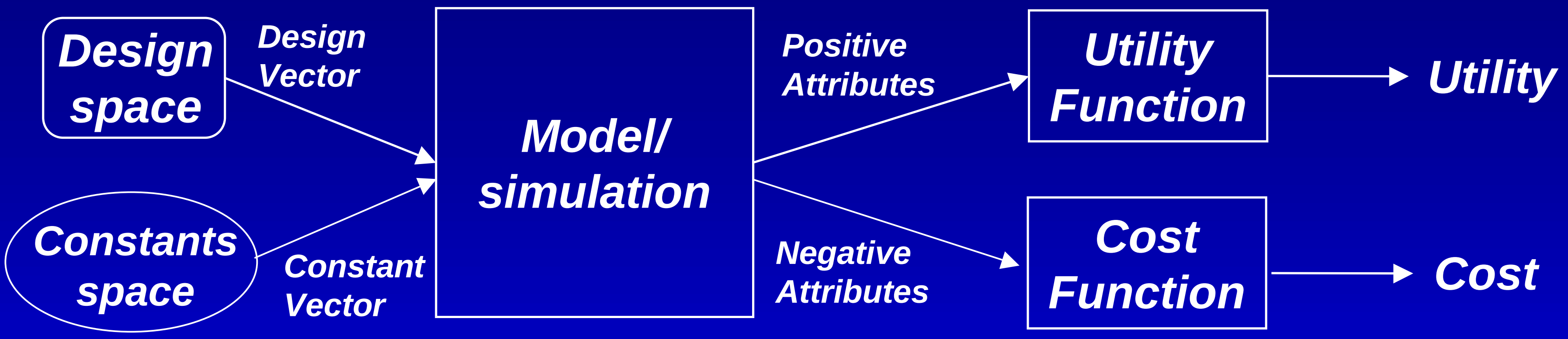
Mothership


Omni antenna
for swarm comm
High gain antenna
for data relay (D ~ 0.5m)
6 omni "whip"
antennae for payload
H = 1.5m
Body mounted
Si solar cells
D = 1.5m
Basic shape can be changed,
assumed cylinder for first iteration

Preliminary Mothership Design Results

- Spacecraft for architecture "C" appears to be feasible.
- Mass was up 17%, and power down 21%, from estimates made as part of the architecture study
- Mothership cost (~$45M) is a significant fraction of the total spacecraft budget (from the architecture study, ~$101M)
- Comm. requirements were severe for TDRSS relay (~10Mbps) and would compete with ISS and Shuttle
- Body mounted solar cell area approaching limit for power needs (~150W)

Extending MAUA For Other Costs



B-TOS