16.89J / ESD.352J Space Systems Engineering
Spring 2007

X-TOS

Preliminary Design Review

May 13, 2002

16.89 Class List

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  Dr. John Ballenthin (AFRL)
  The Aerospace Corp.

Class Mission Statements

- The purpose of 16.89 is to actively explore the concept of Systems Engineering
- Team members work collaboratively using a newly developed, structured design process

Process is as important as results!

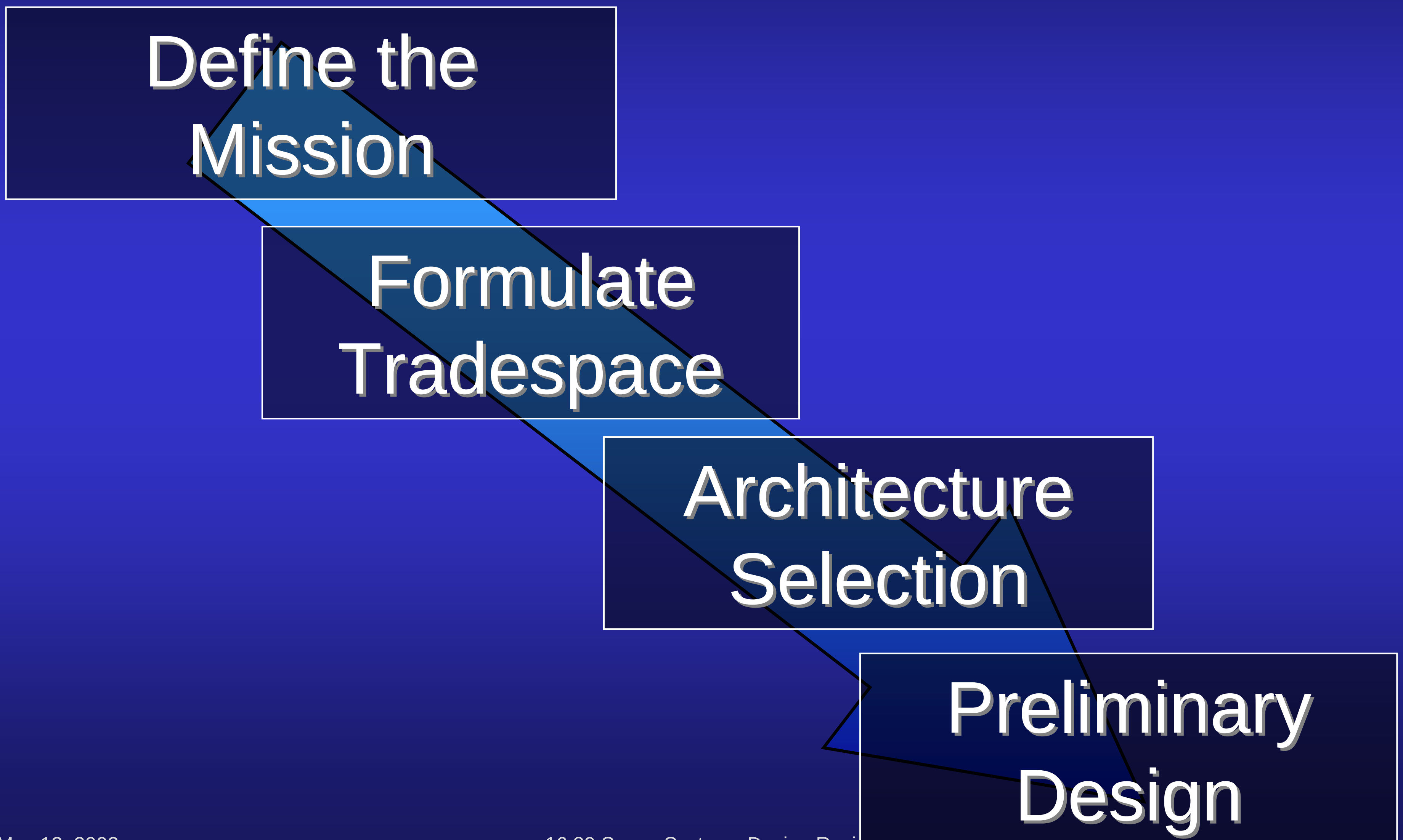
Value Proposition

- **Students:**
  - Learn about space systems design
  - Gain experience through the design of a space system architecture and satellite
  - Present AFRL with an architecture analysis and preliminary design
- Professors:
  - Guide the students through the process
  - Utilize experience to help students learn
  - Present AFRL with an architecture analysis and preliminary design
- AFRL:
  - Provide a real system for students to gain experience
  - Receive an architectural analysis and preliminary design

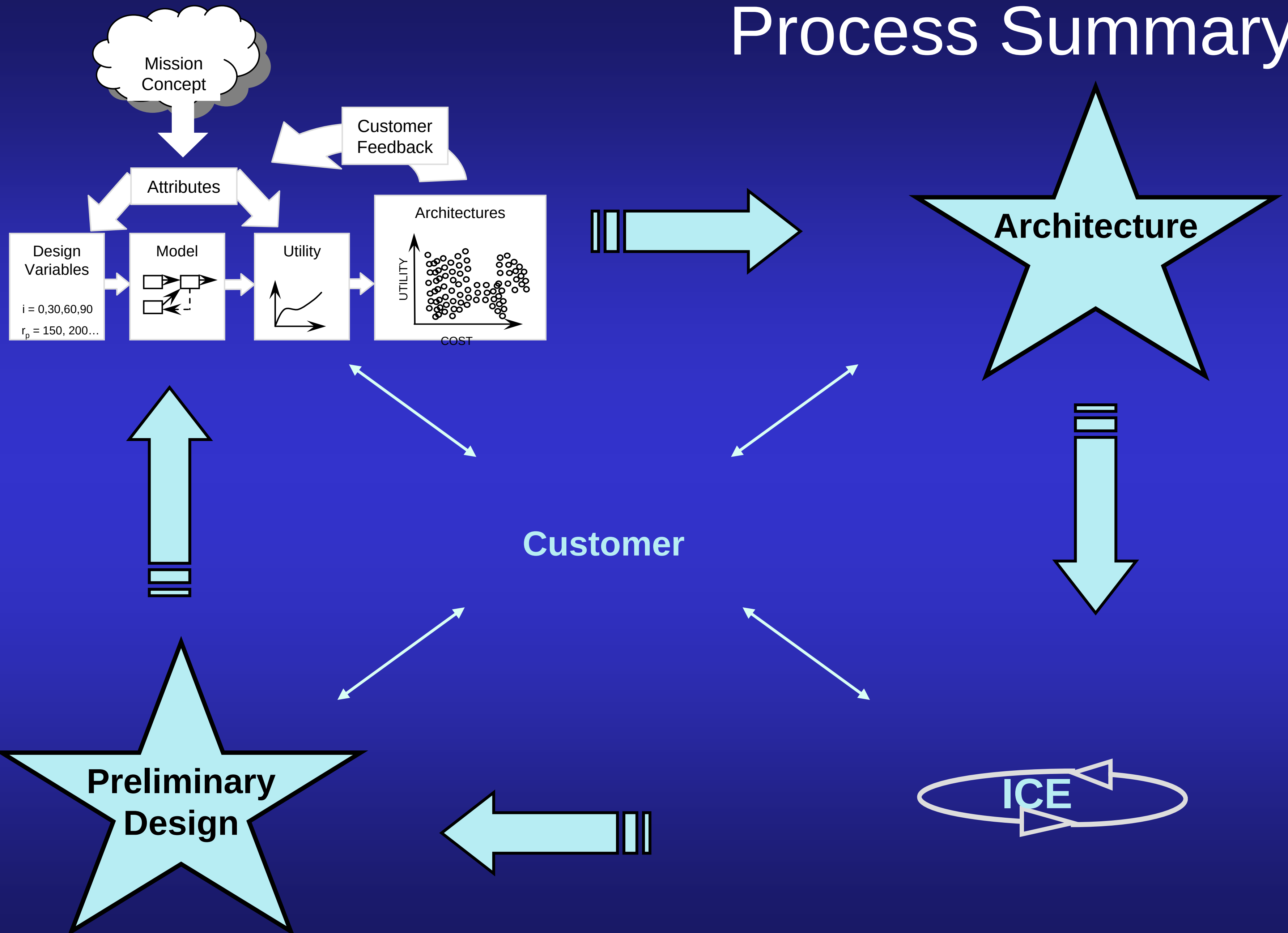
Traditional Design Methodology

- Identify Need
- Talk to the Customer
- Research
- Brainstorm Potential Solutions
- Choose Point Design
- Build
- Test
- Sell

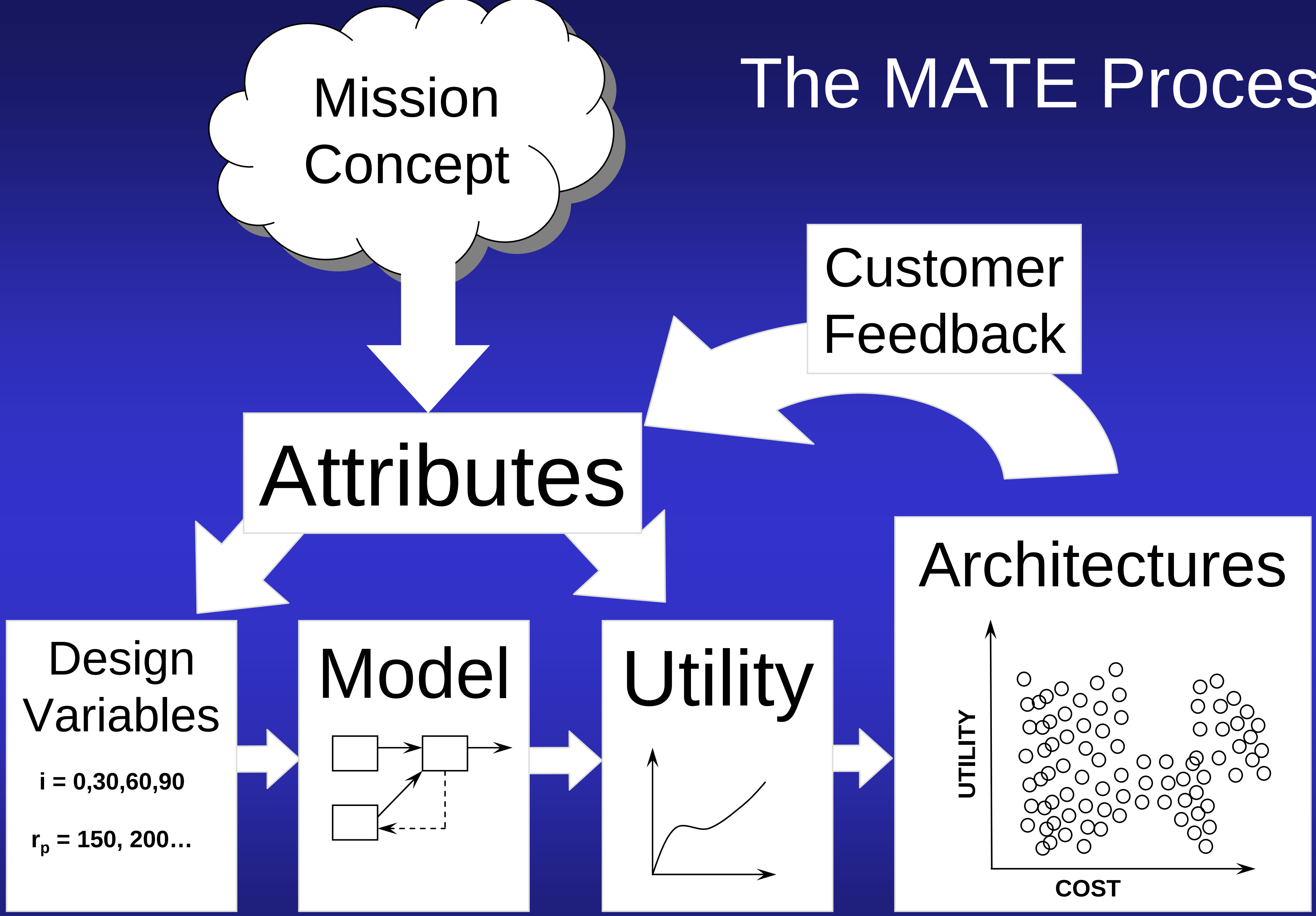
16.89 Class Process



Process Summary



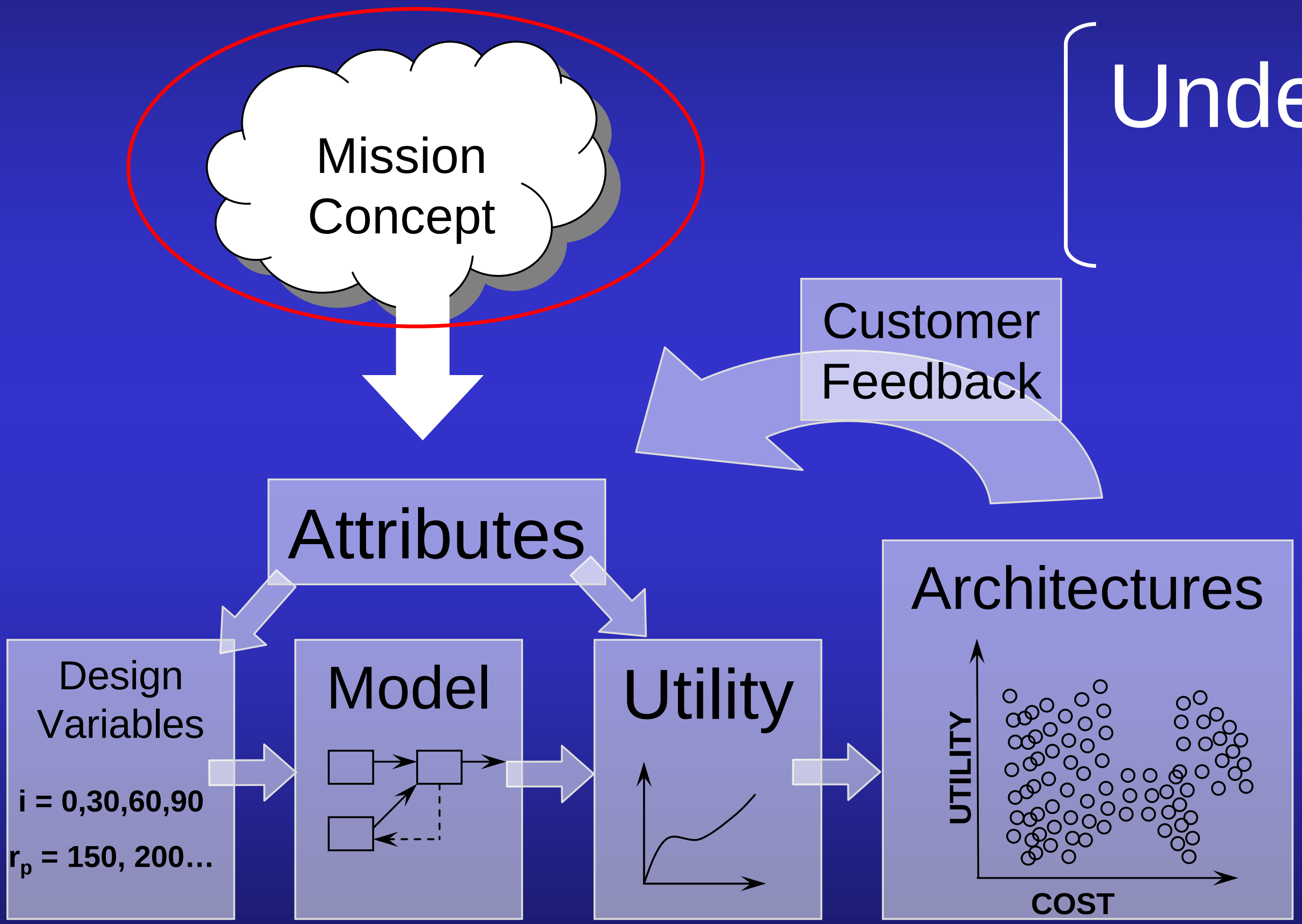
The MATE Process



Multi-Attribute Tradespace Exploration

MATE Process Check

Understand the Mission



Drag and Reentry Prediction - Mir

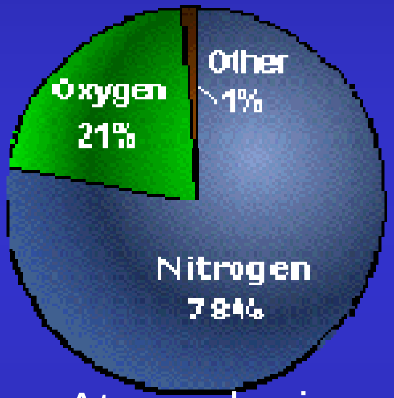
10% error along the orbital path translates to nearly 6500 km on the ground!

Map of Mir Debris Footprint removed due to copyright restrictions.

Image from Aerospace Corporation

Atmospheric Drag

- Satellites traveling through the atmosphere encounter drag forces due to neutral particles
- Density and composition of particles varies with :
  - – altitude
  - – geographic location
  - – solar radiation
  - – geomagnetic activity

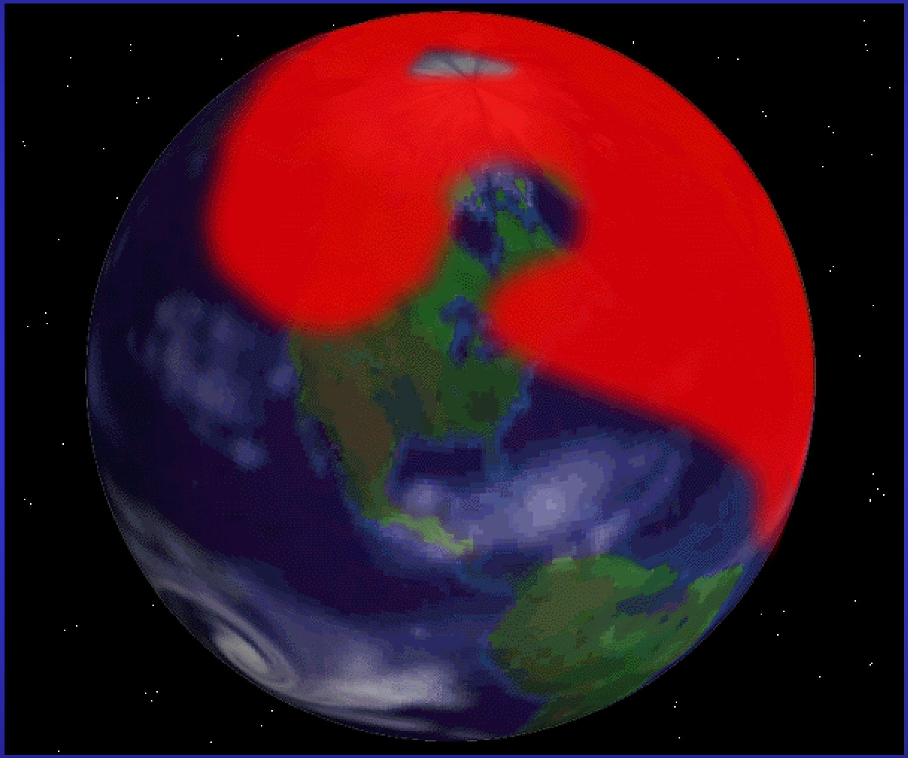


Atmospheric Composition

Prediction of drag effects on spacecraft traveling through the atmosphere is highly uncertain

Drag Modeling and Prediction

- During certain solar cycles or magnetic storms, atmospheric density can increase as much as 100% (shown in red at right)
- These disturbances cause thousands of objects to alter their predicted orbits. These objects must be "found" again by tracking stations



Mission Description

- The Air Force Research Lab's *Space Vehicles Branch* needs data to develop satellite drag and neutral density models

- The models will enable:
  - Precision orbit predictions for high interest satellites
  - Re-entry prediction
  - Positioning of AF surveillance satellites
  - Collision avoidance
  - Cataloging space debris orbits

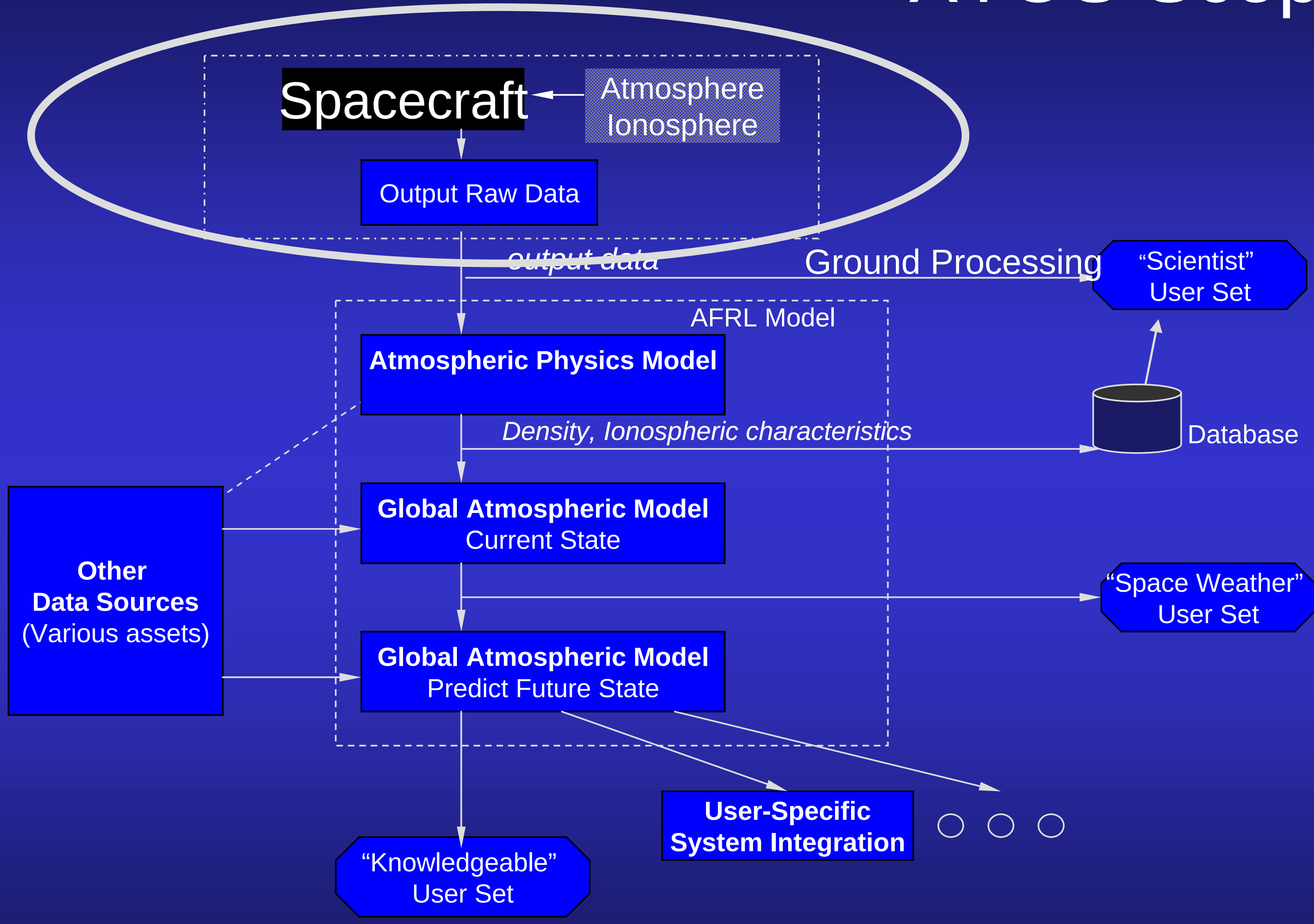
Mission Payload

- The data will be obtained by flying the customer's instrument suite through the upper atmosphere

ADS MEASUREMENTS

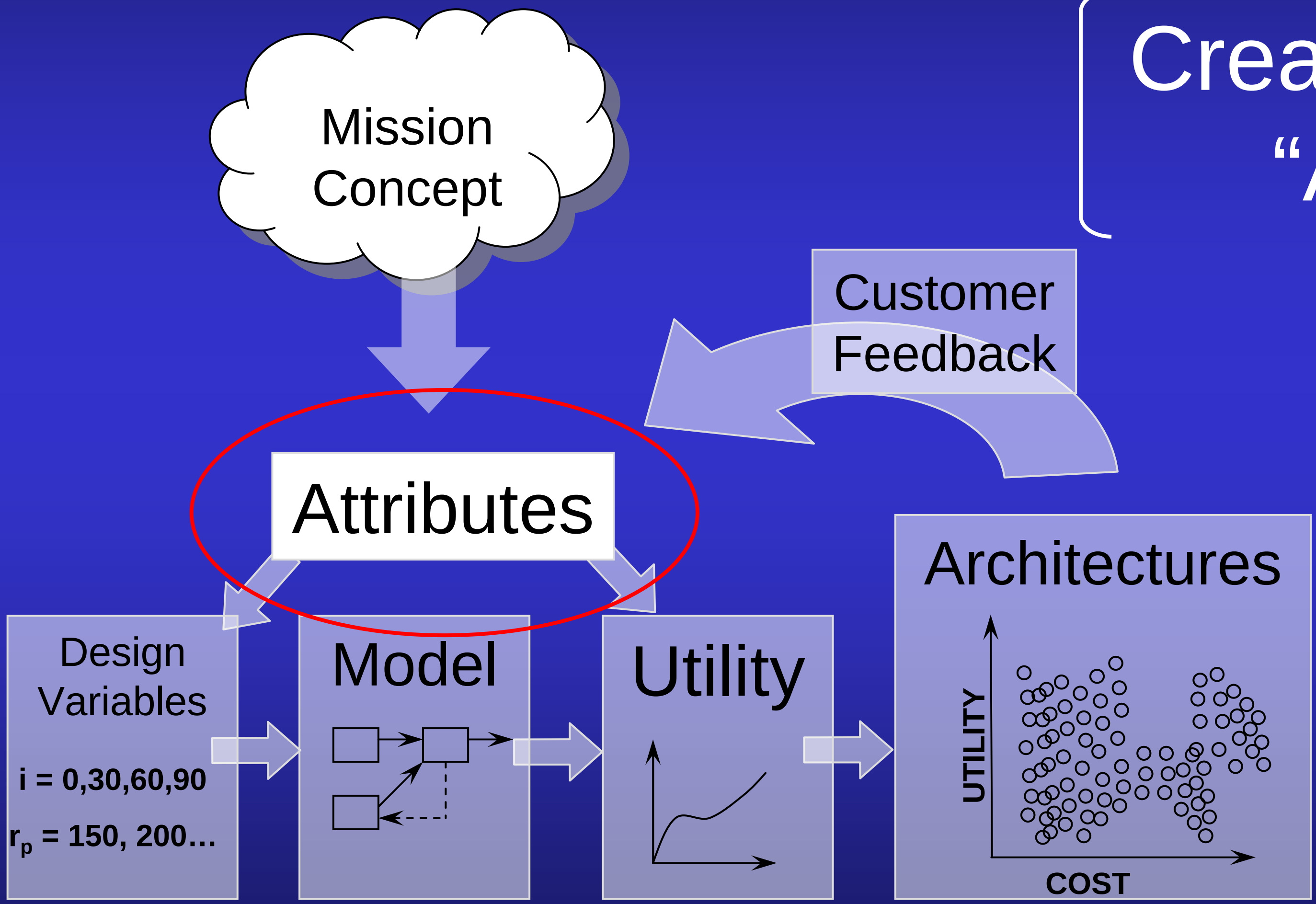
- **Satellite Drag**
- **Neutral Density**
- **Neutral Winds**
- **Neutral Composition**
- **Ion Composition**
- **Temperature**

XTOS Scope


Spacecraft
Atmosphere
Ionosphere
Output Raw Data
output data
Ground Processing
"Scientist"
User Set
AFRL Model
Atmospheric Physics Model
Database
Density, Ionospheric characteristics
Other
Data Sources
(Various assets)
Global Atmospheric Model
Current State
"Space Weather"
User Set
Global Atmospheric Model
Predict Future State
User-Specific
System Integration
"Knowledgeable"
User Set

MATE Process Check

Create a list of "Attributes"



Practical Constraints

- Fly AFRL-provided instrument package
- Instruments Ram-Facing within 0.1 degrees
- Knowledge of altitude accurate to within 250 meters
- Launched from a U.S vehicle / launch site
- Communications through TDRSS or AFSCN

User Preferences

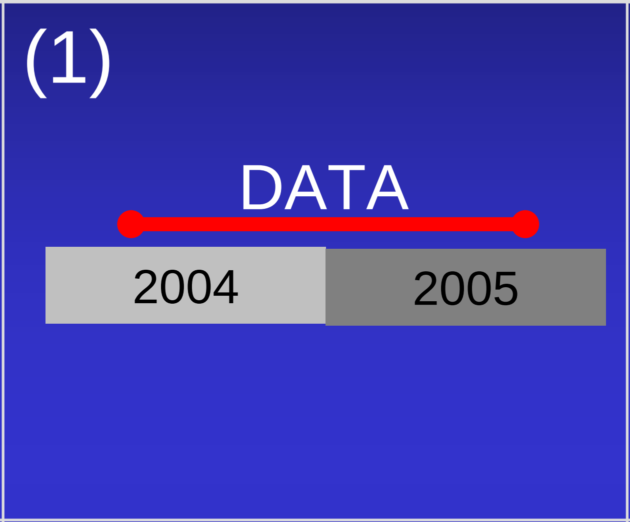
- Data samples taken over wide range of latitudes
- Data collected over different solar and earth weather cycles
  - (e.g. solar max/min, night/day, etc…)
- Distribution of data points (across latitudes, time cycles)
- Mission lifetime greater than 6 months

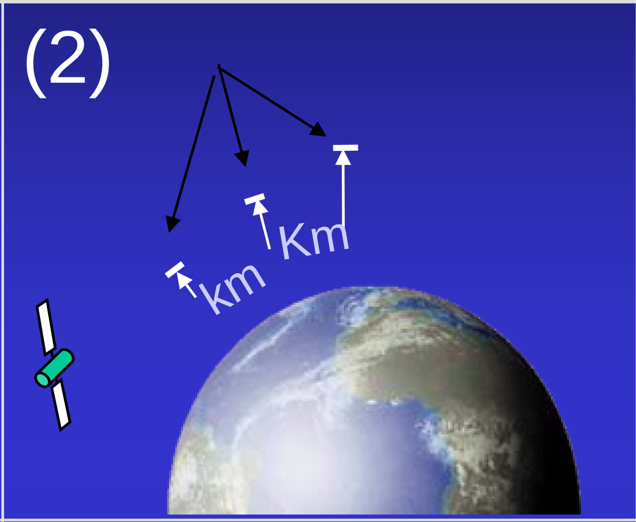
What is an attribute?

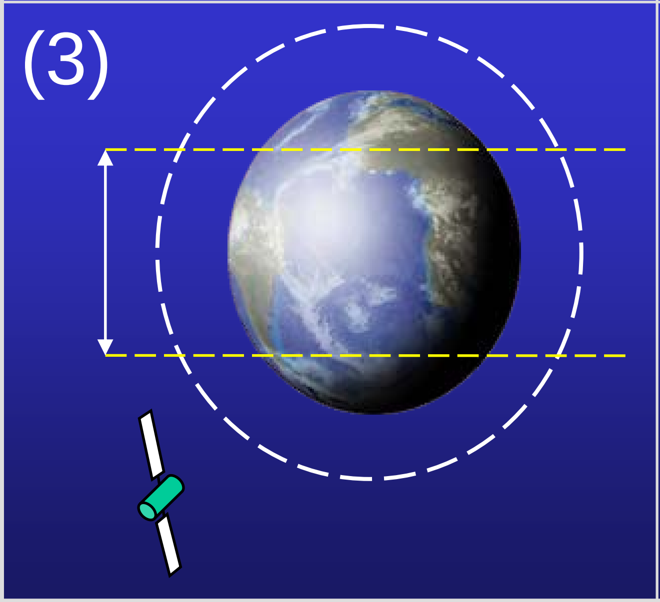
- Quantifiable variable capable of measuring how well a *<u>user-defined</u>* objective is met
- Set of attributes must be:
  - Complete
  - Operational
  - Decomposable
  - Non-redundant
  - Minimal
  - Independent of cost
- "Rule of 7" Human mind limited to roughly 7 simultaneous concepts

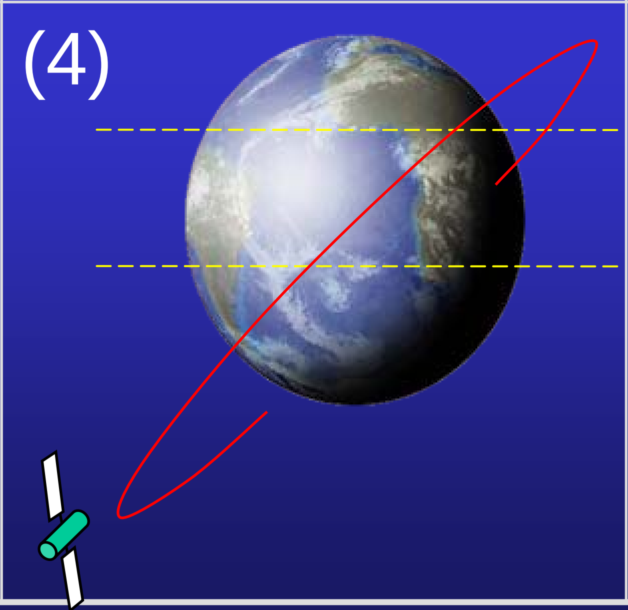
Attributes

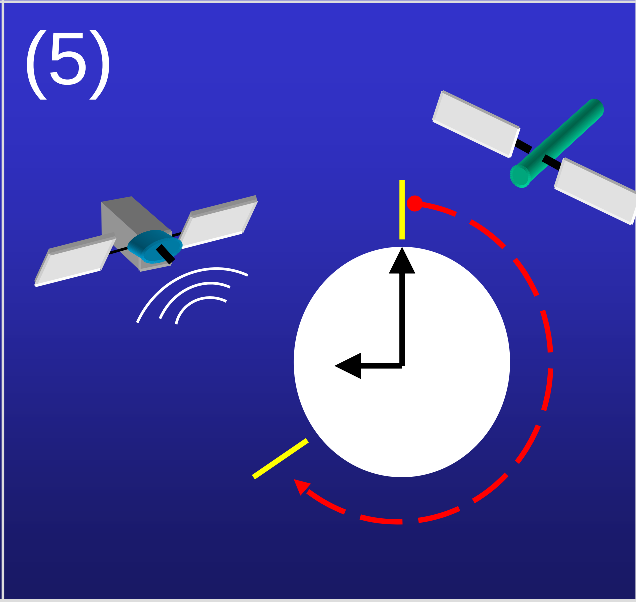
1) Data Life Span
2) Data Altitude
3) Maximum Latitude
4) Time Spent at Equator
5) Data Latency





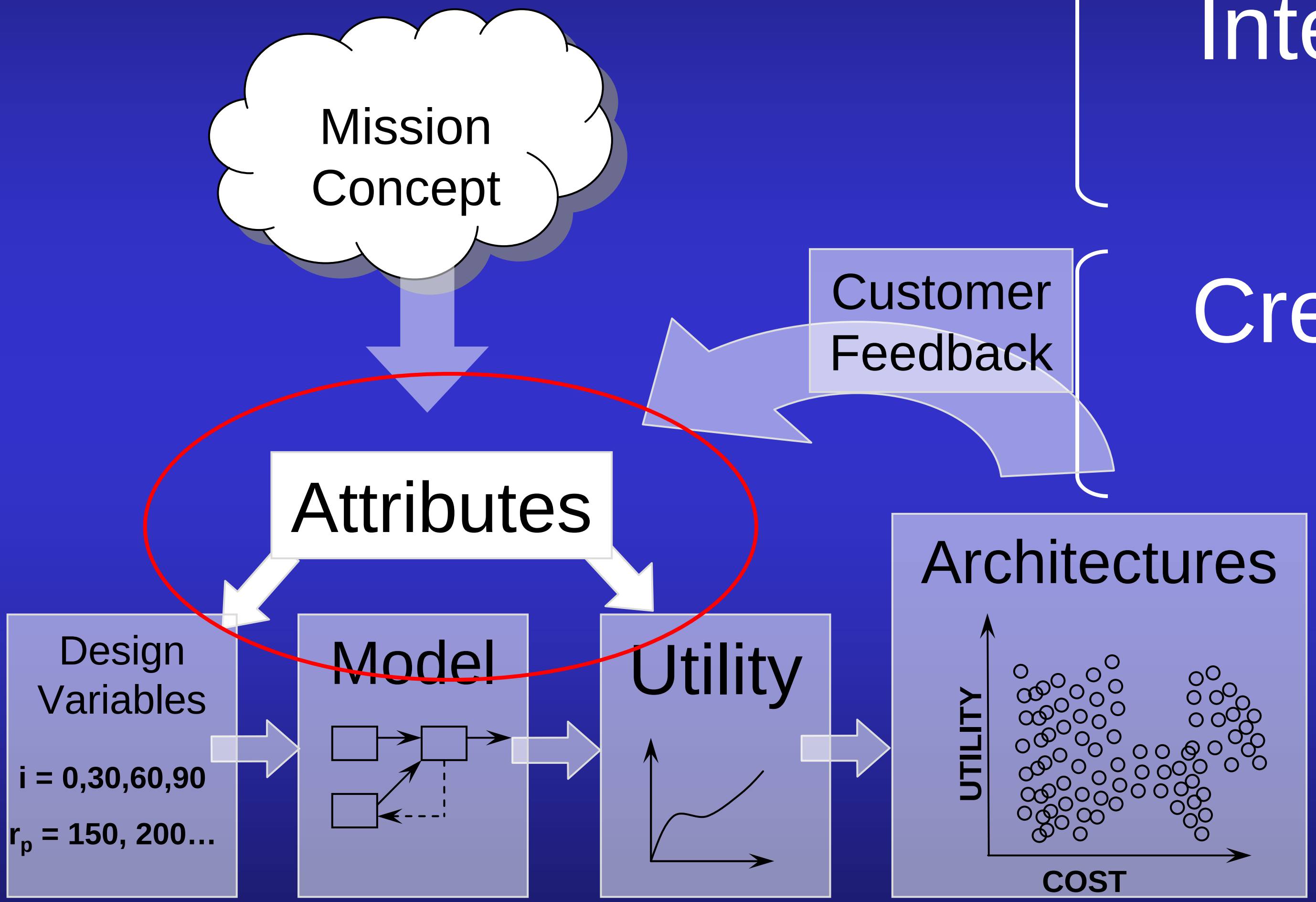






MATE Process Check

- Interview the Customer
- Create Utility Curves

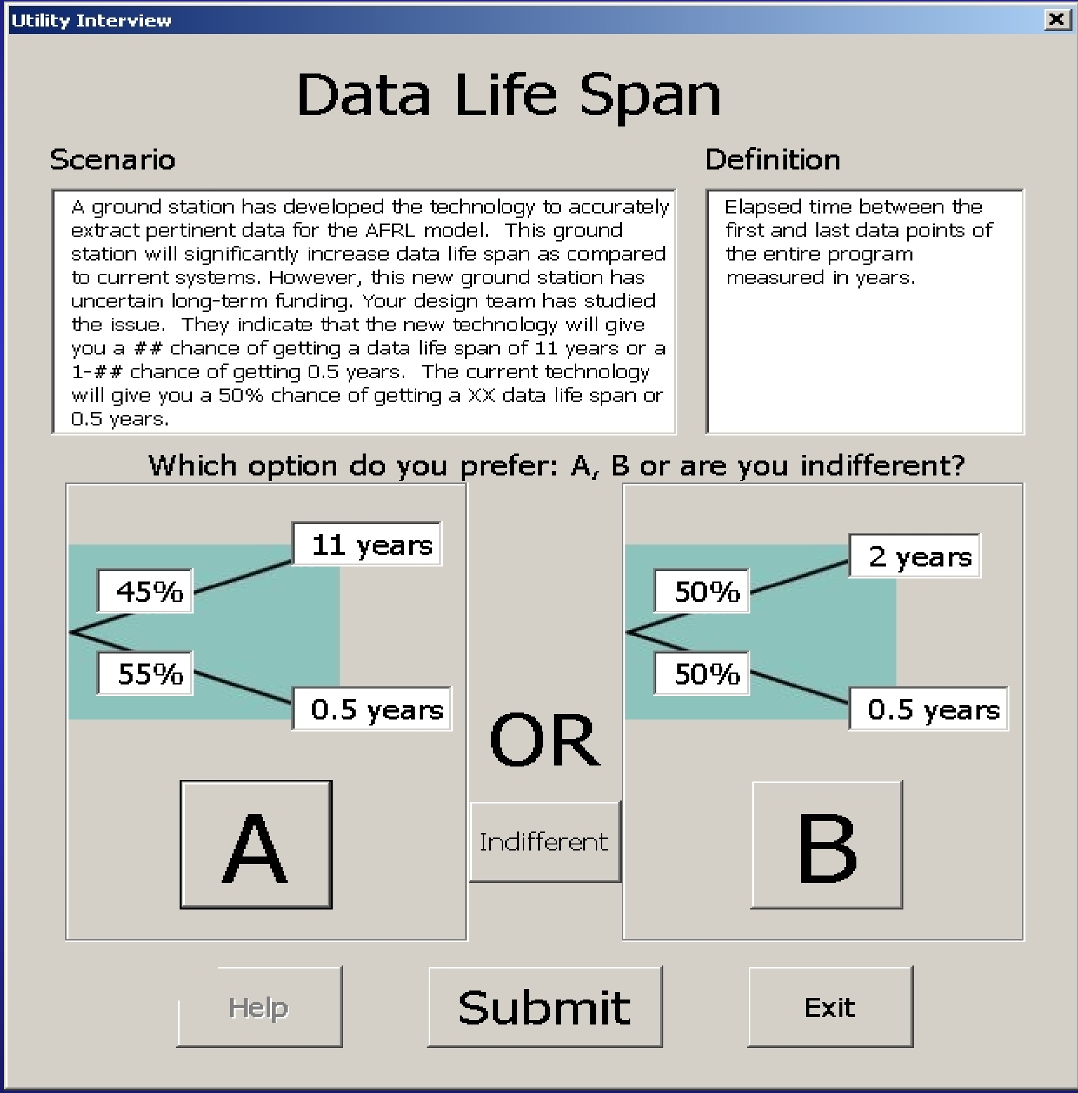


What is Utility?

- Mathematical measure of “goodness”—lifted from Economics
- Ranges from 0 – 1: Ordered Metric scale
- Involved in the interview process and “multi-attribute utility theory”
- Allows us to expand the possibilities for design and trade one attribute against another

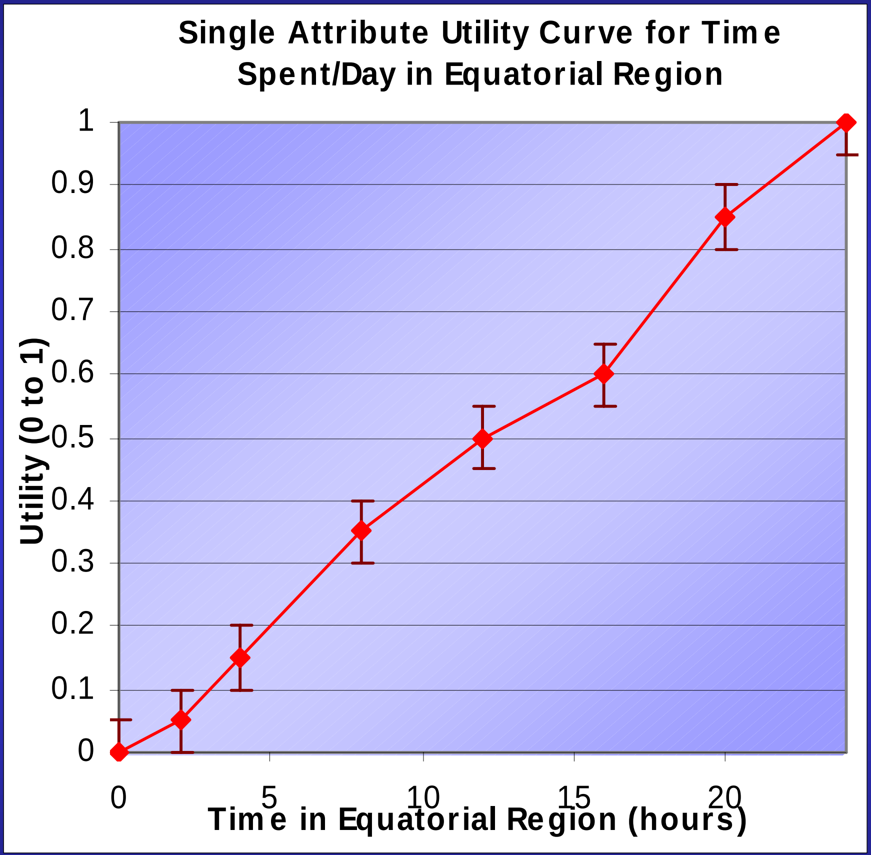
Multi-Attribute Interview Software Tool (MIST)

- Attributes framed by "scenarios"—meant to take each attribute in isolation
- MIST uses the "lottery equivalent probability" to create a utility curve
- User first rates each attribute individually, then balances each against the others

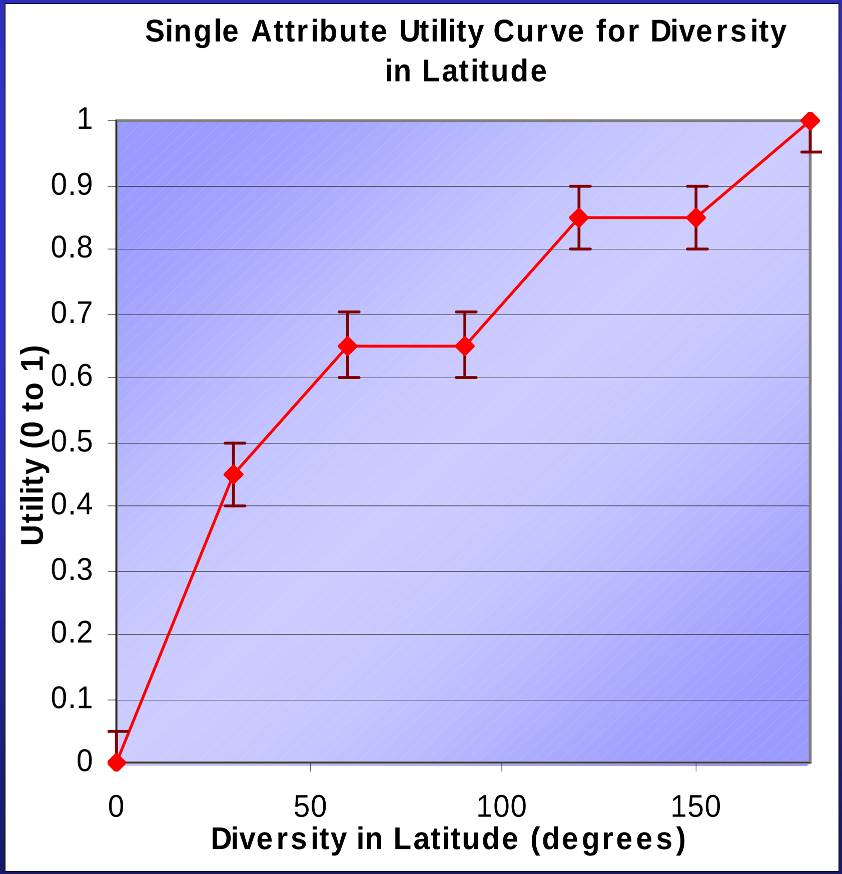


*MIST created by Satwik Seshasai

Converting Attributes to Utility Curves



- Sometimes users do not show a linear preference over an attribute



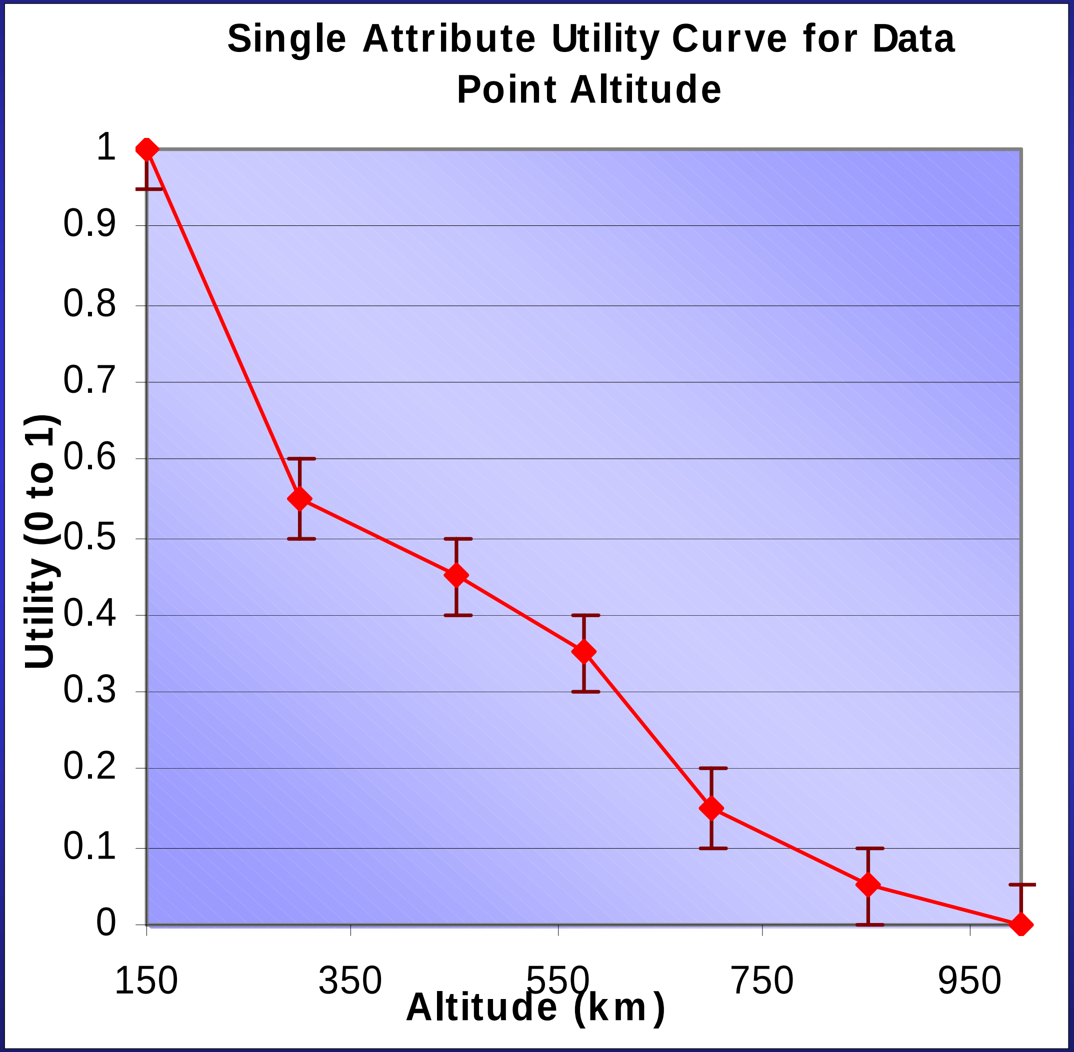
- Different curve for each attribute
- Combination of attribute values produces overall utility

Abstracting and Calculating Utility

- Propagated over entire orbit to get utility of orbit $\overline{U}$

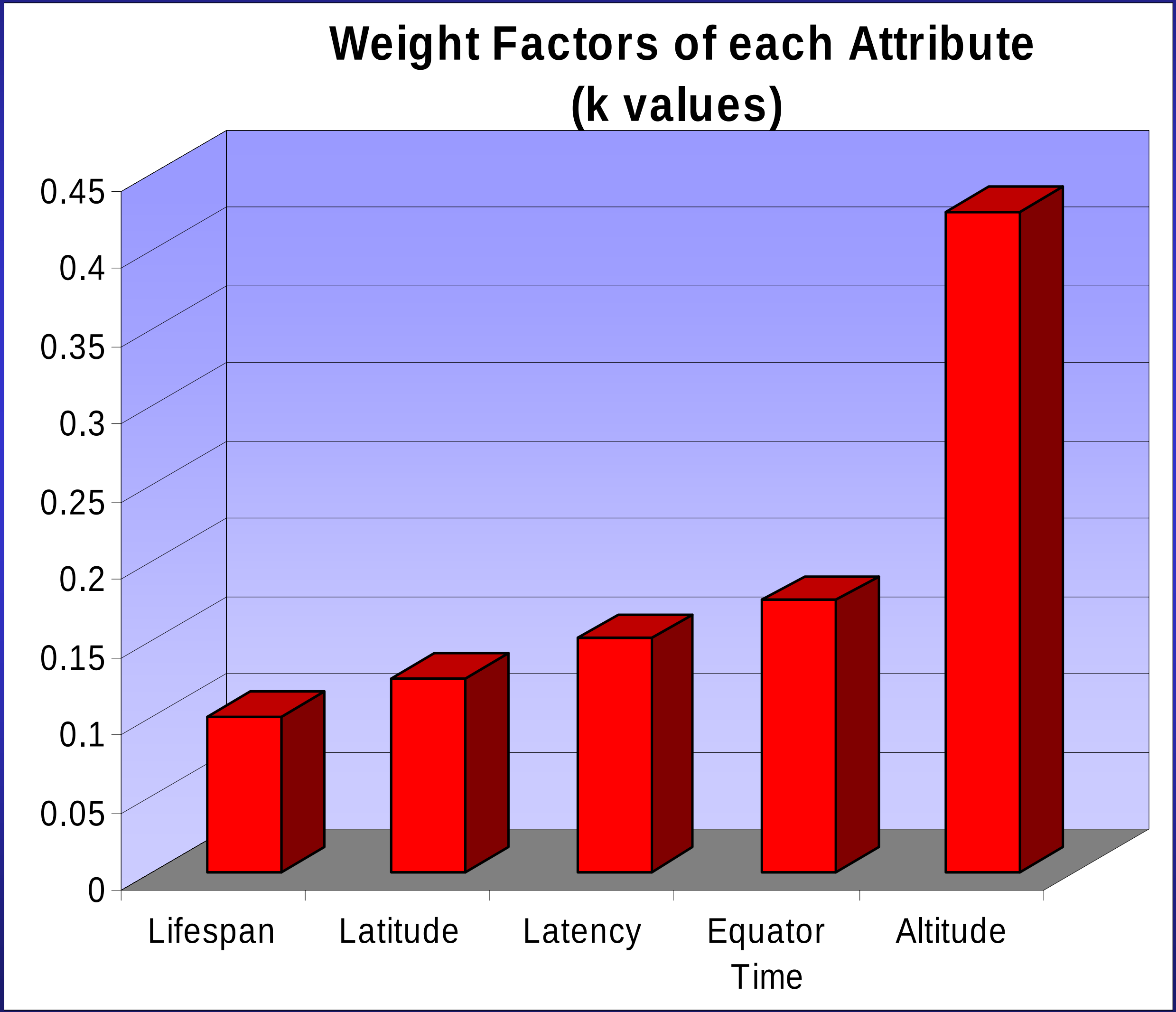
$$\overline{U} = \frac{\sum_{i=1}^{n} U\left(h(t_i)\right)}{n}$$

Time step = 1 minute



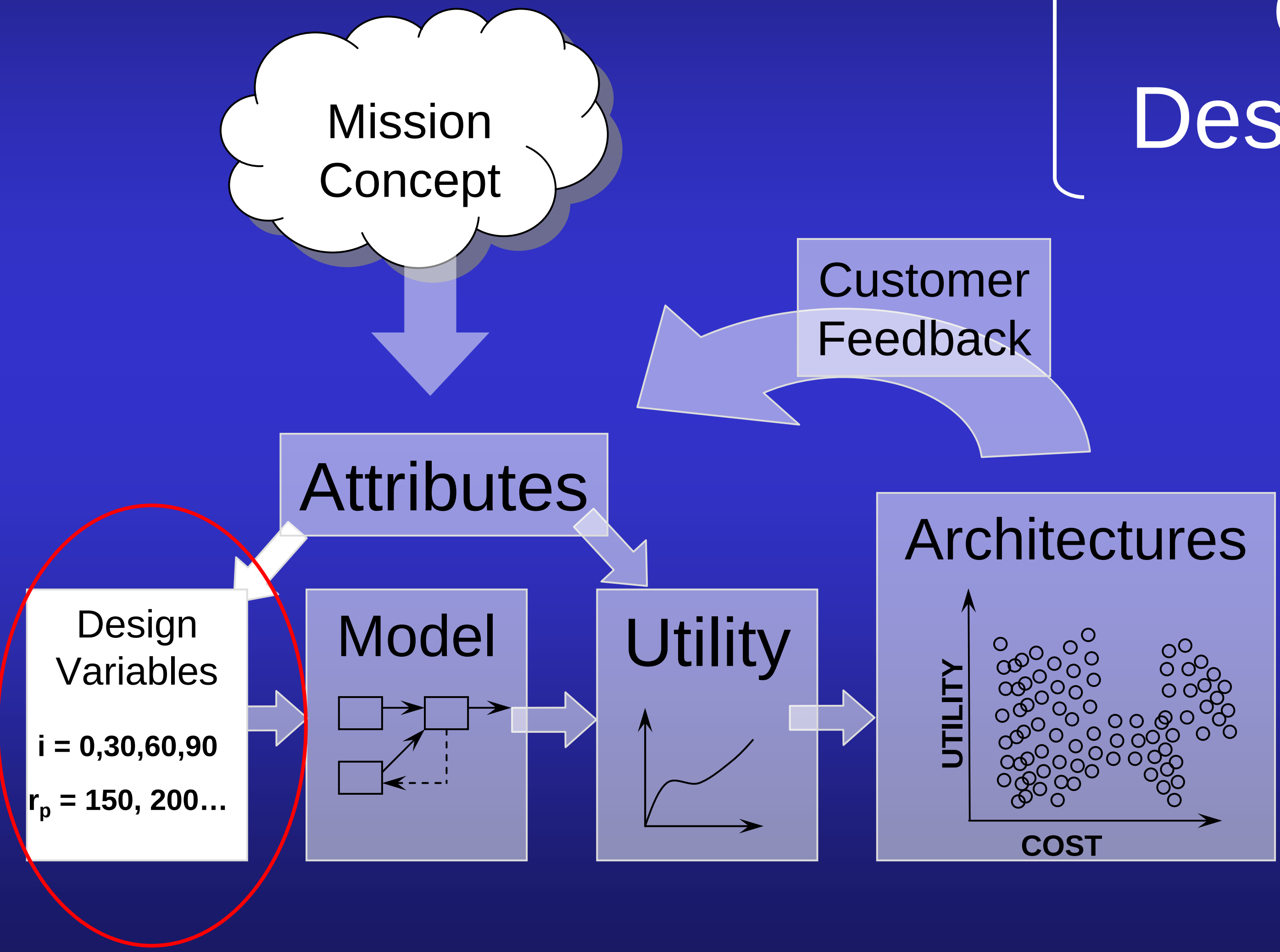
Attribute Weighting Factors

- Depicts the relative importance of each attribute to the user
- Resolution of ±0.025



MATE Process Check

Create the Design Vector



Design Vector Overview

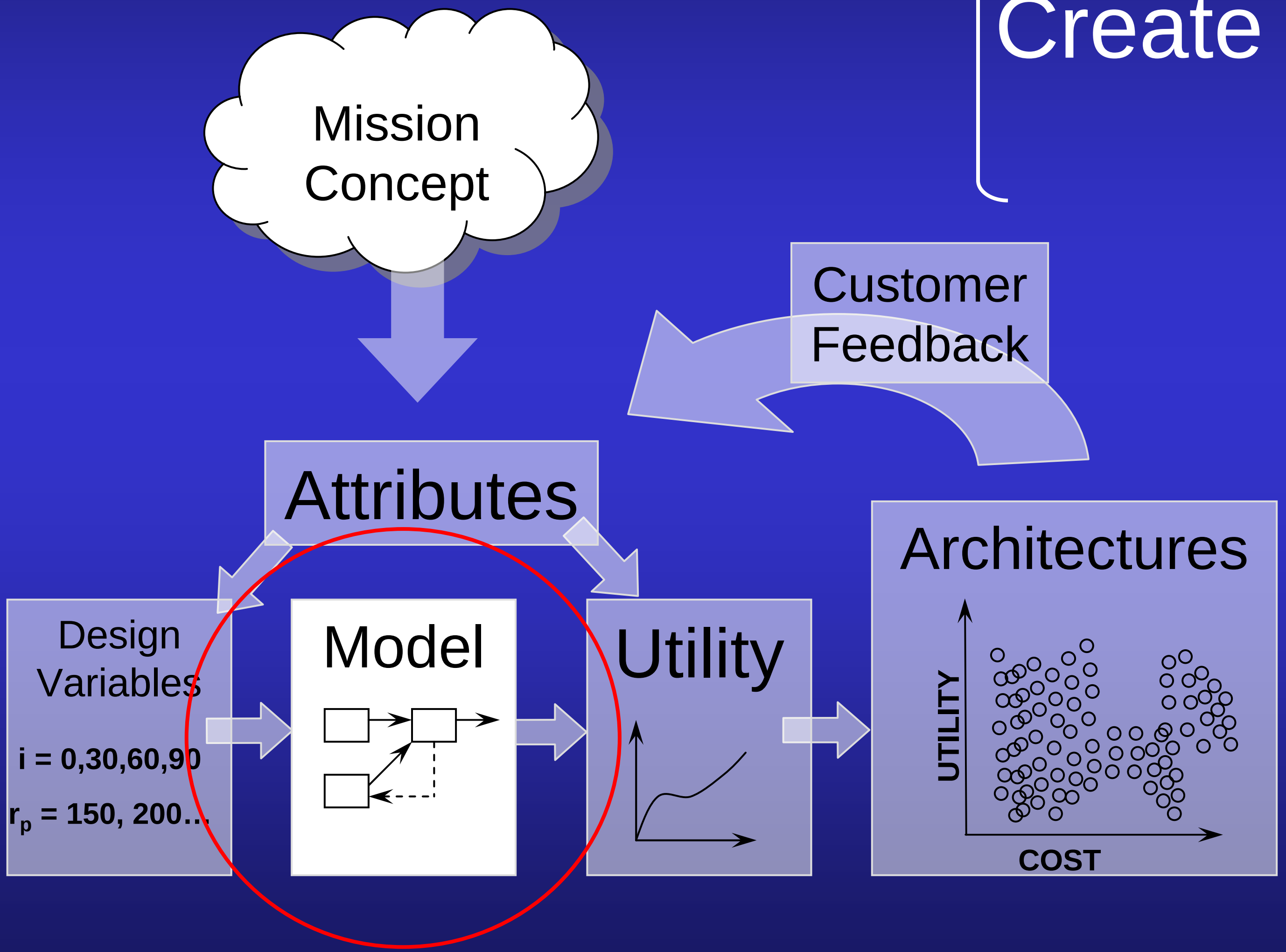
- Independent design variables that have a significant impact on attributes (design knobs)
- Design vector excludes model constants
- Design vector provides a means to consider multitudes of architectures
- Geometric growth of combinations limits size, scope

Design Vector

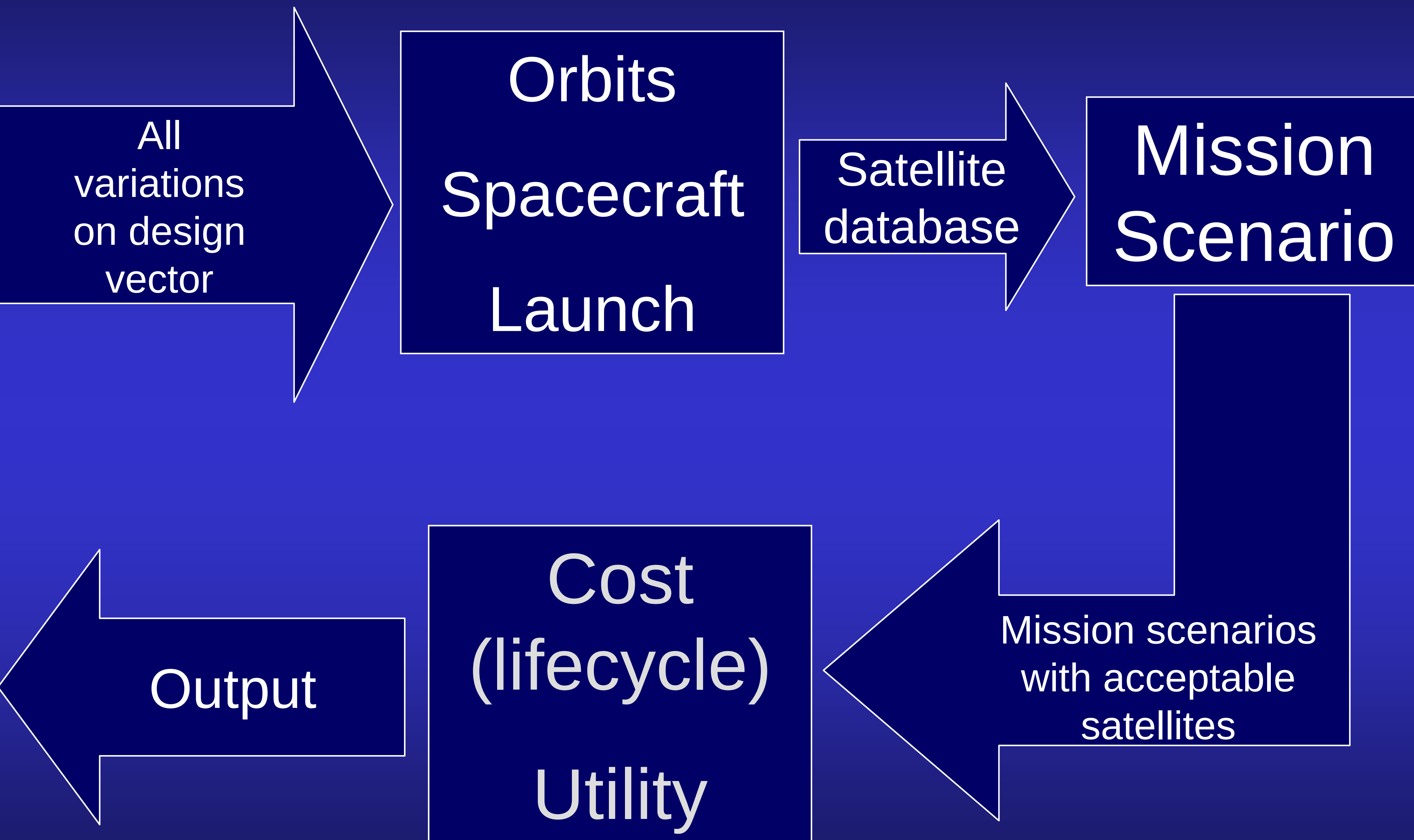
Variable:	First Order Effect:
Orbital Parameters:	
•Apogee altitude (200 to 2000 km)	Lifetime, Altitude
•Perigee altitude (150 to 350 km)	Lifetime, Altitude
•Orbit inclination (0 to 90 degrees)	Lifetime, Altitude
	Latitude Range
	Time at Equator
Physical Spacecraft Parameters:	
•Antenna gain (low/high)	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

MATE Process Check

Create Simulation Software

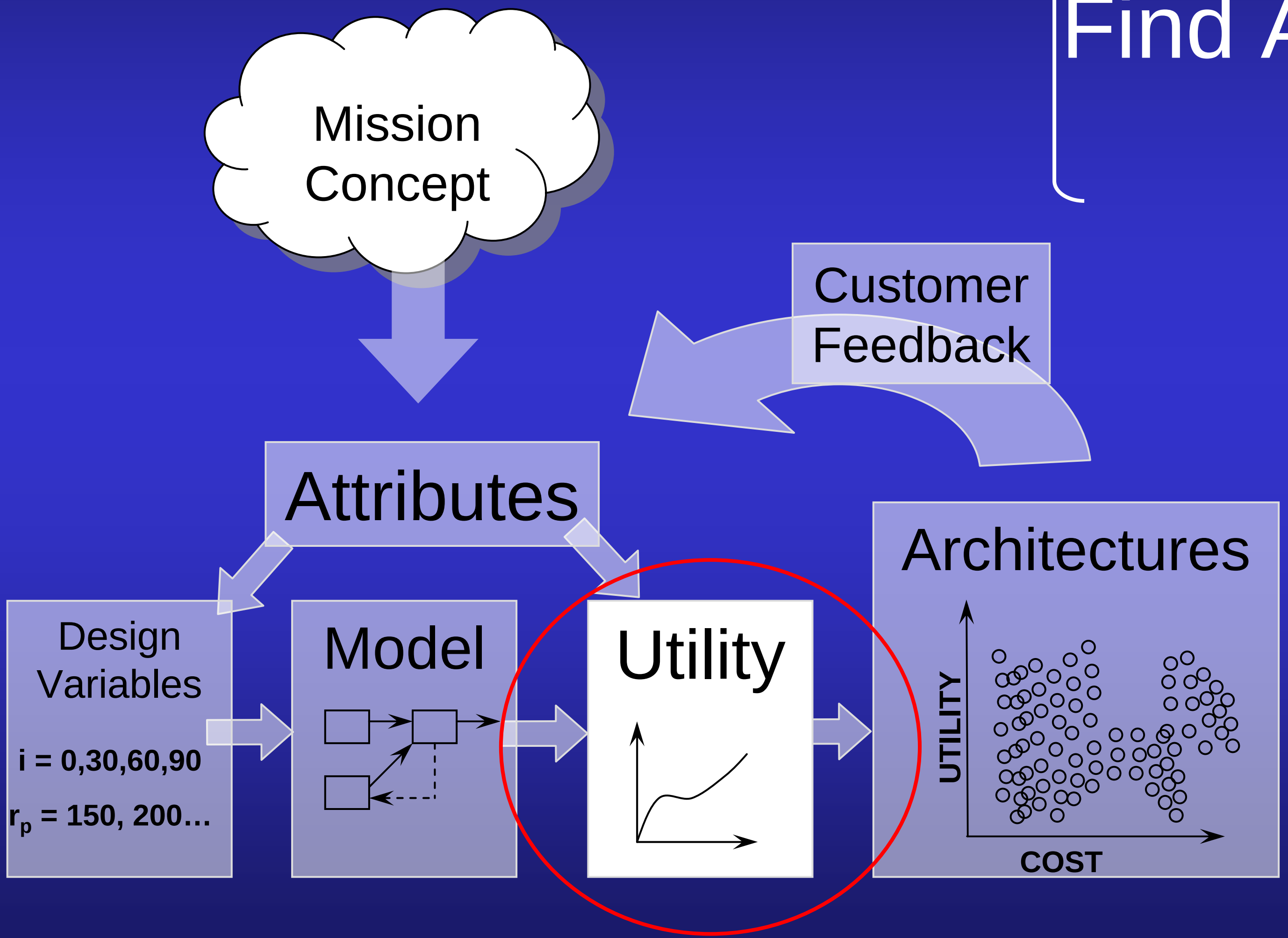


Simulation Software Flow Chart



MATE Process Check

Find Architecture Utility



Multi-Attribute Utility Process

Stage 1: Calculate Attributes

1. Determine mission scenario and satellites used
2. Divide mission scenario into “phases”, where a new phase denotes a change in attribute values.
3. Calculate the specific attribute values from the satellites involved in each phase

Multi-Attribute Utility Process

Stage 2: Utility Function

1. Calculate Multi-Attribute Utility Value (MAUV) for each phase (see below)
2. Average MAUV using a time weighted average of the phases

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

*Keeney, Raiffa, 1976.

Normalization constant

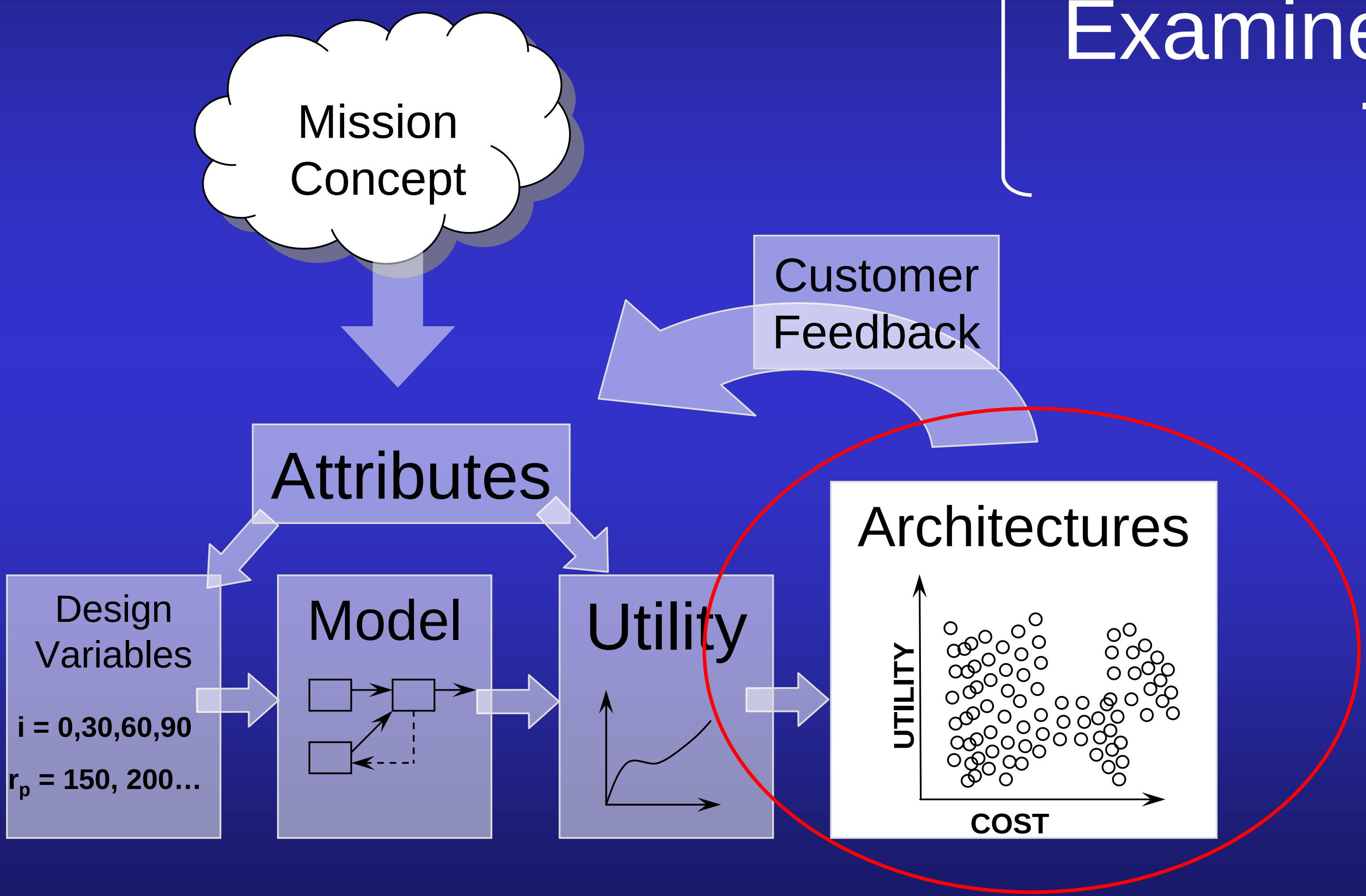
Multi-attribute utility function

Relative “weight”

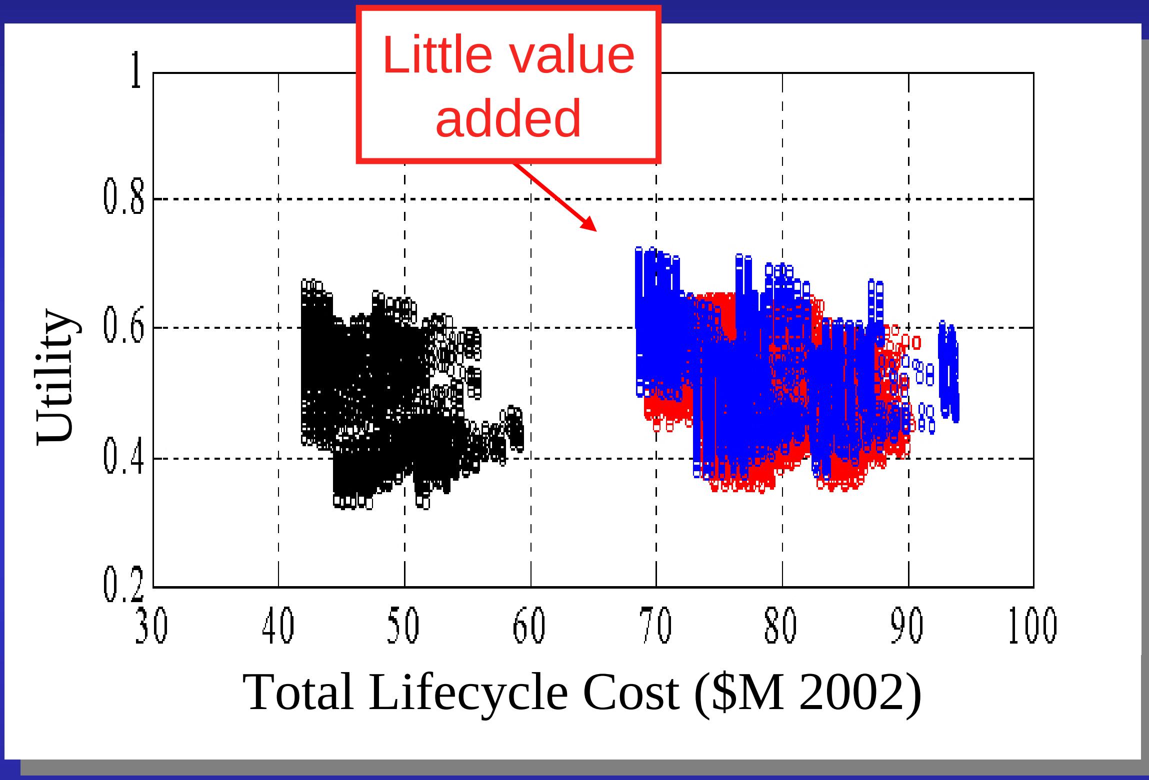
Single attribute utility

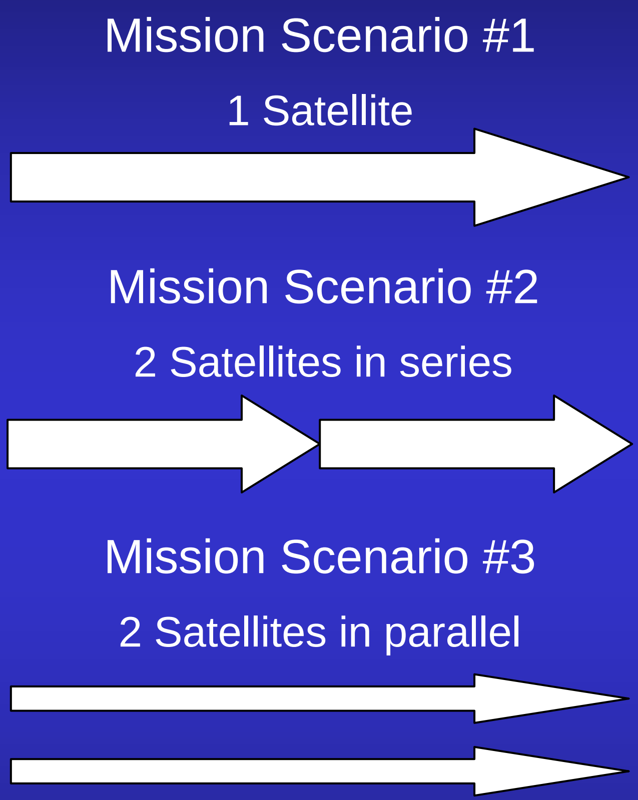
MATE Process Check

Examine Utility Trades



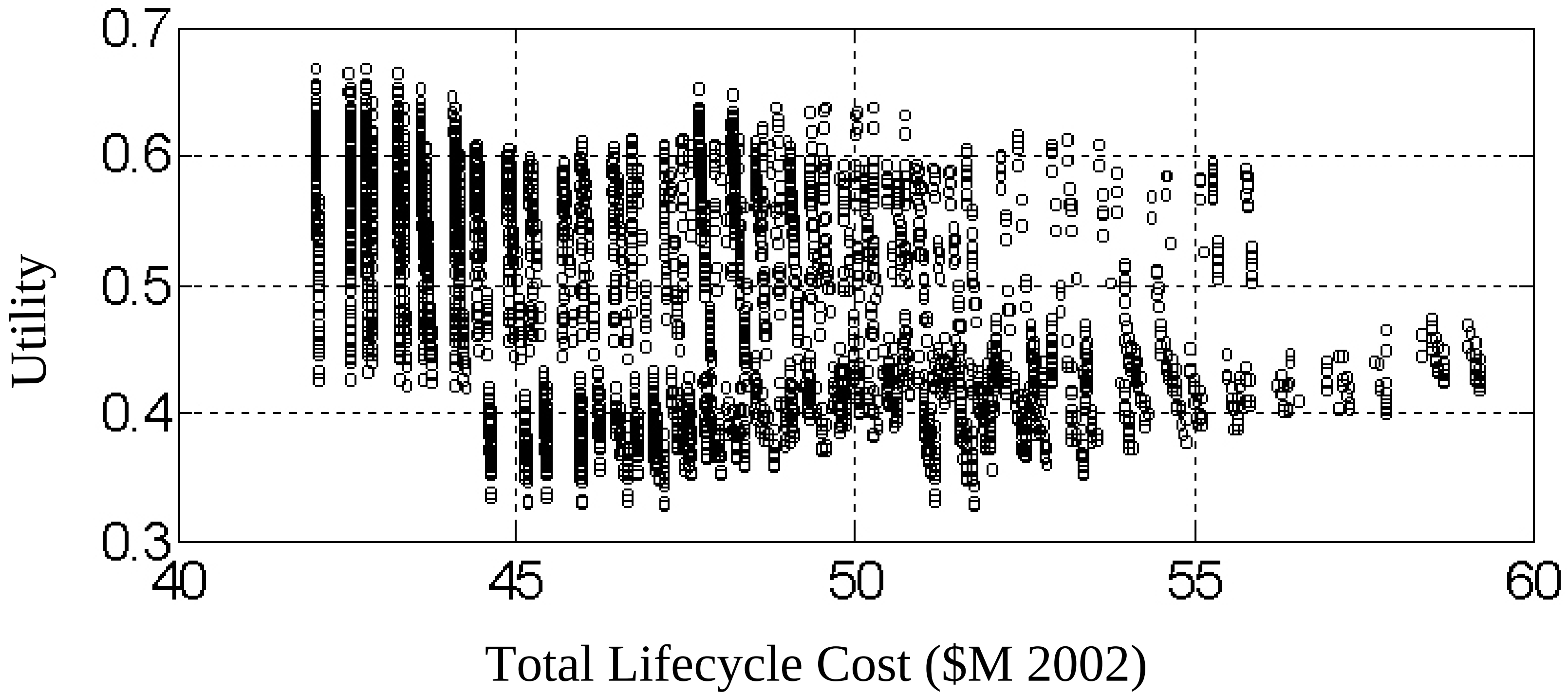
All Architectures





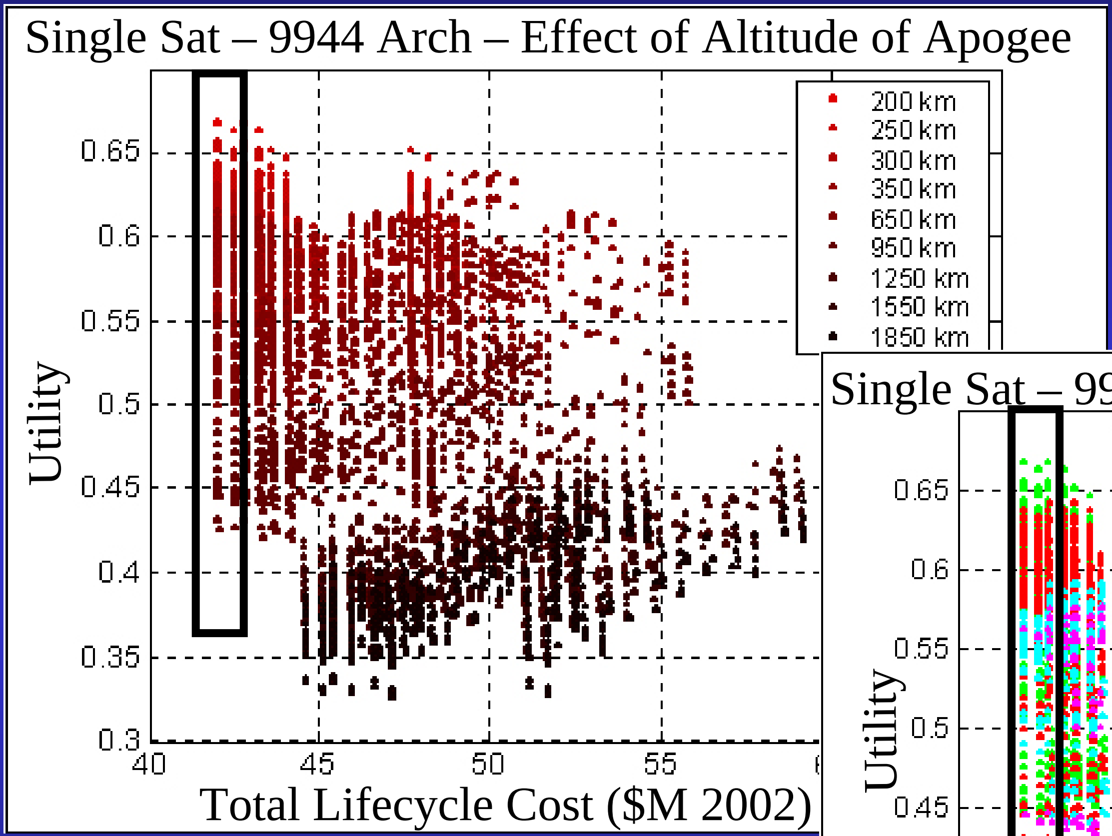
- Single satellite – 9944 architectures
- Two satellites launched in series – 20000 arch
- Two satellites launched in parallel – 20544 arch

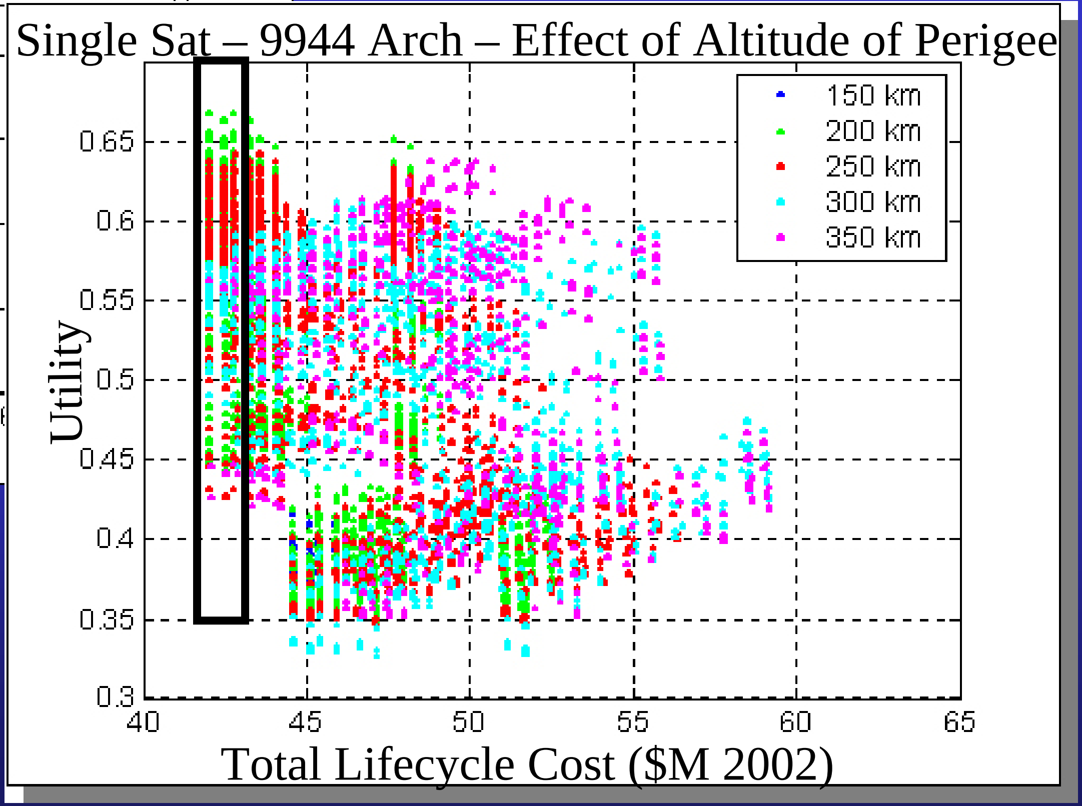
Scenario 1: Single Satellite



- Single satellite – 9944 architectures

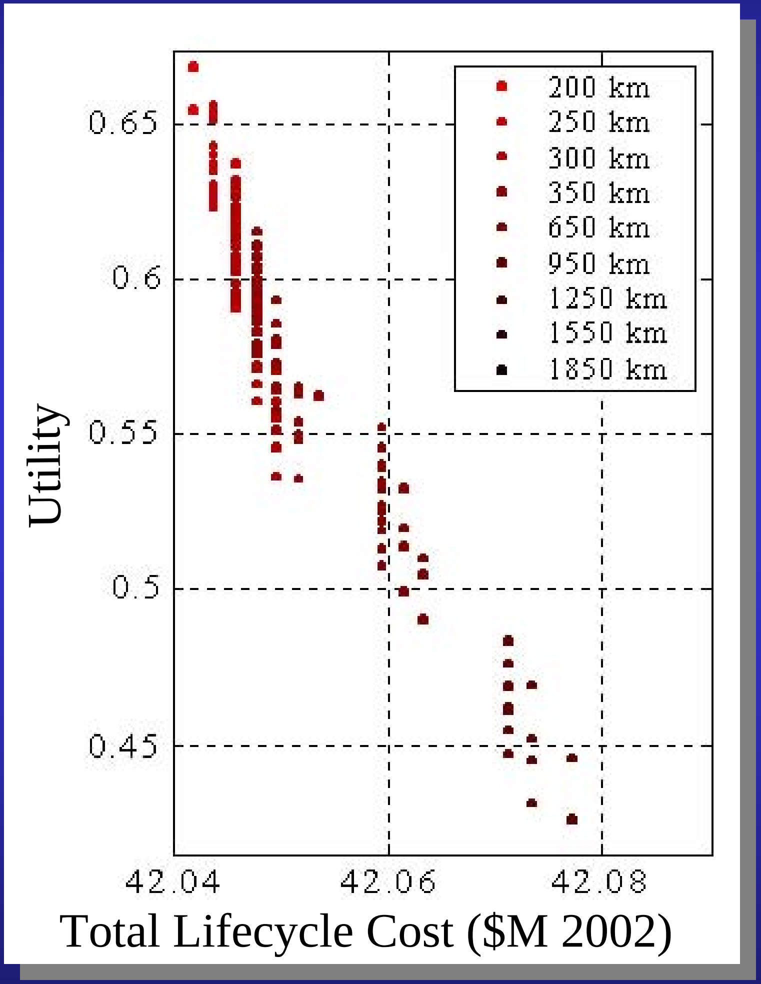
Utility vs. Cost with Altitude



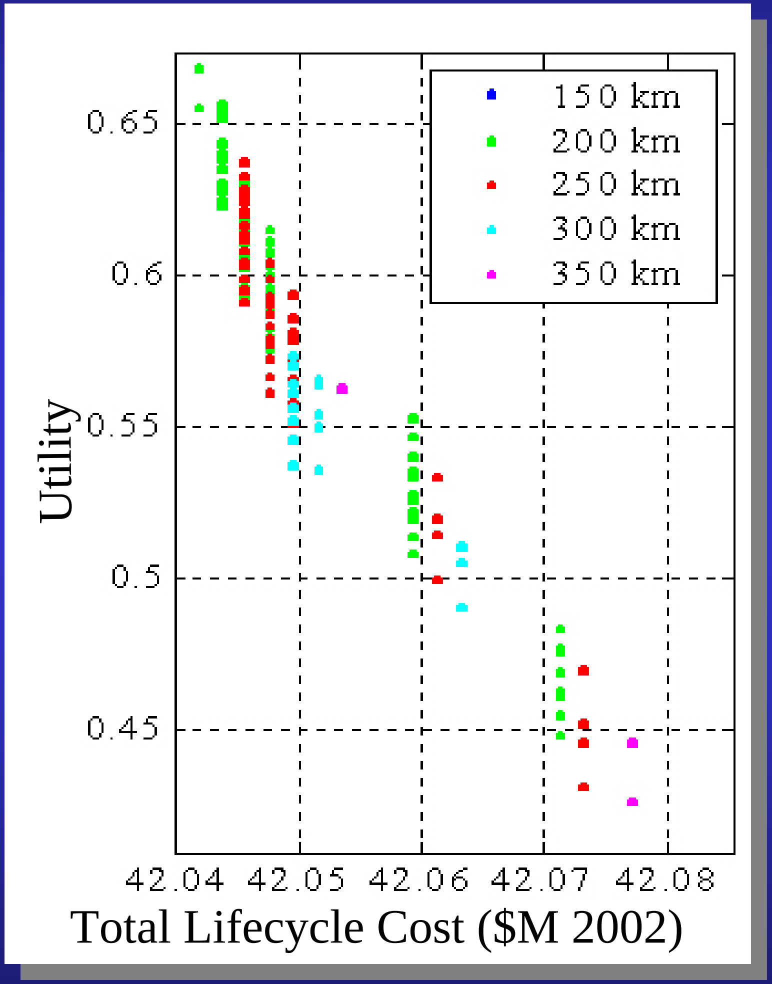


Zoom in on black box

Apogee

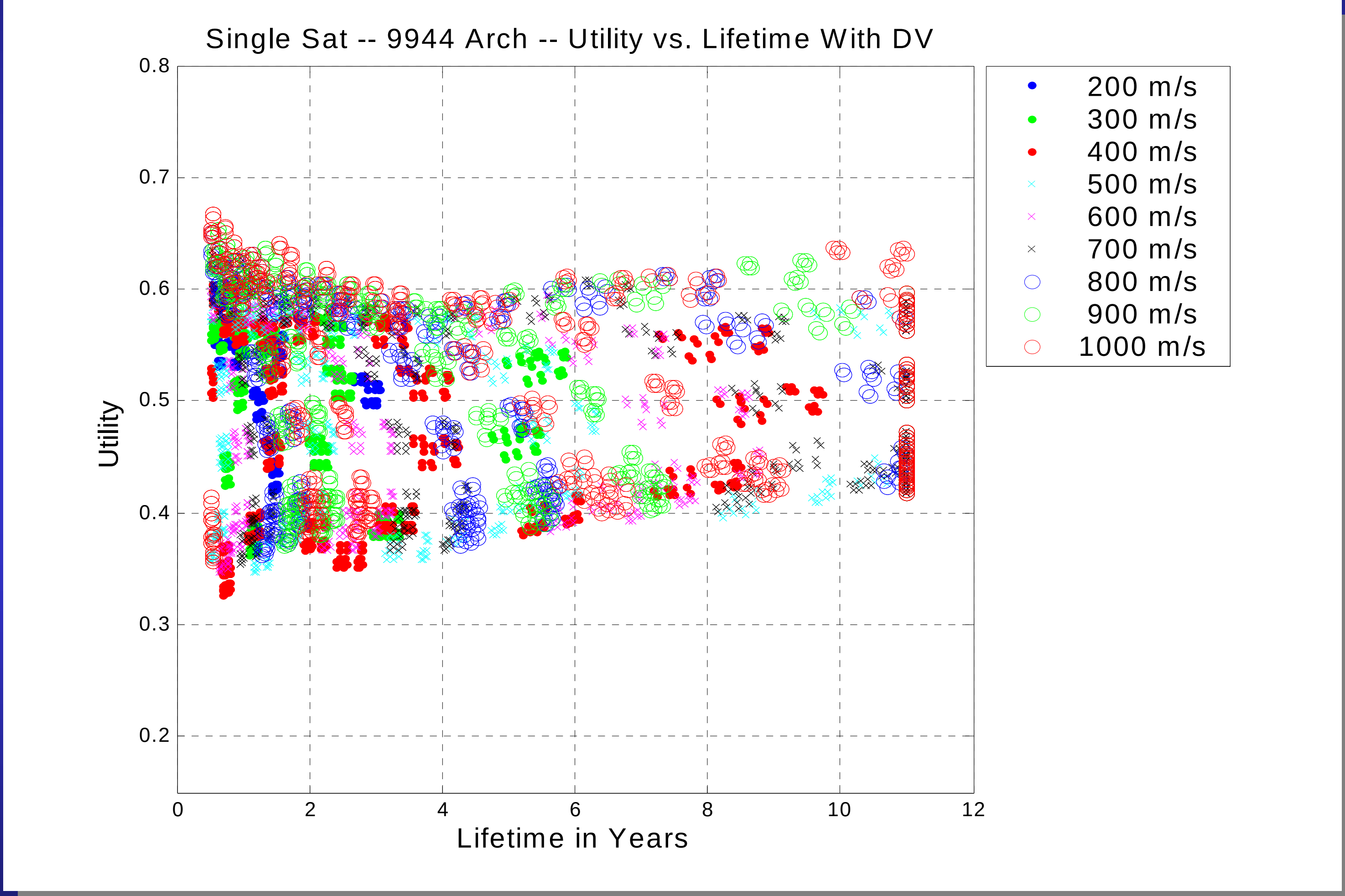


Perigee



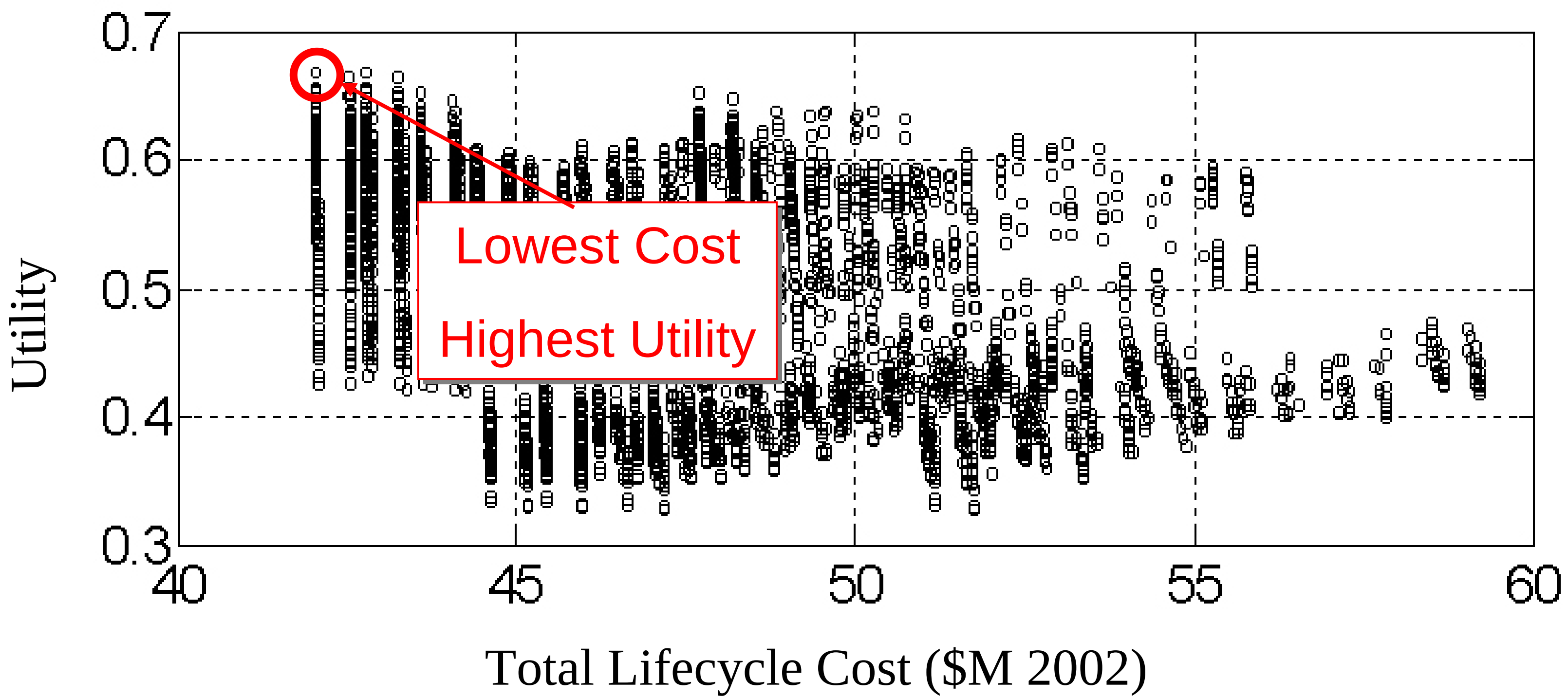
Apogee is the main driver, perigee is secondary

Utility vs. Lifetime With ΔV



ΔV is secondary driver

Scenario 1: Single Satellite



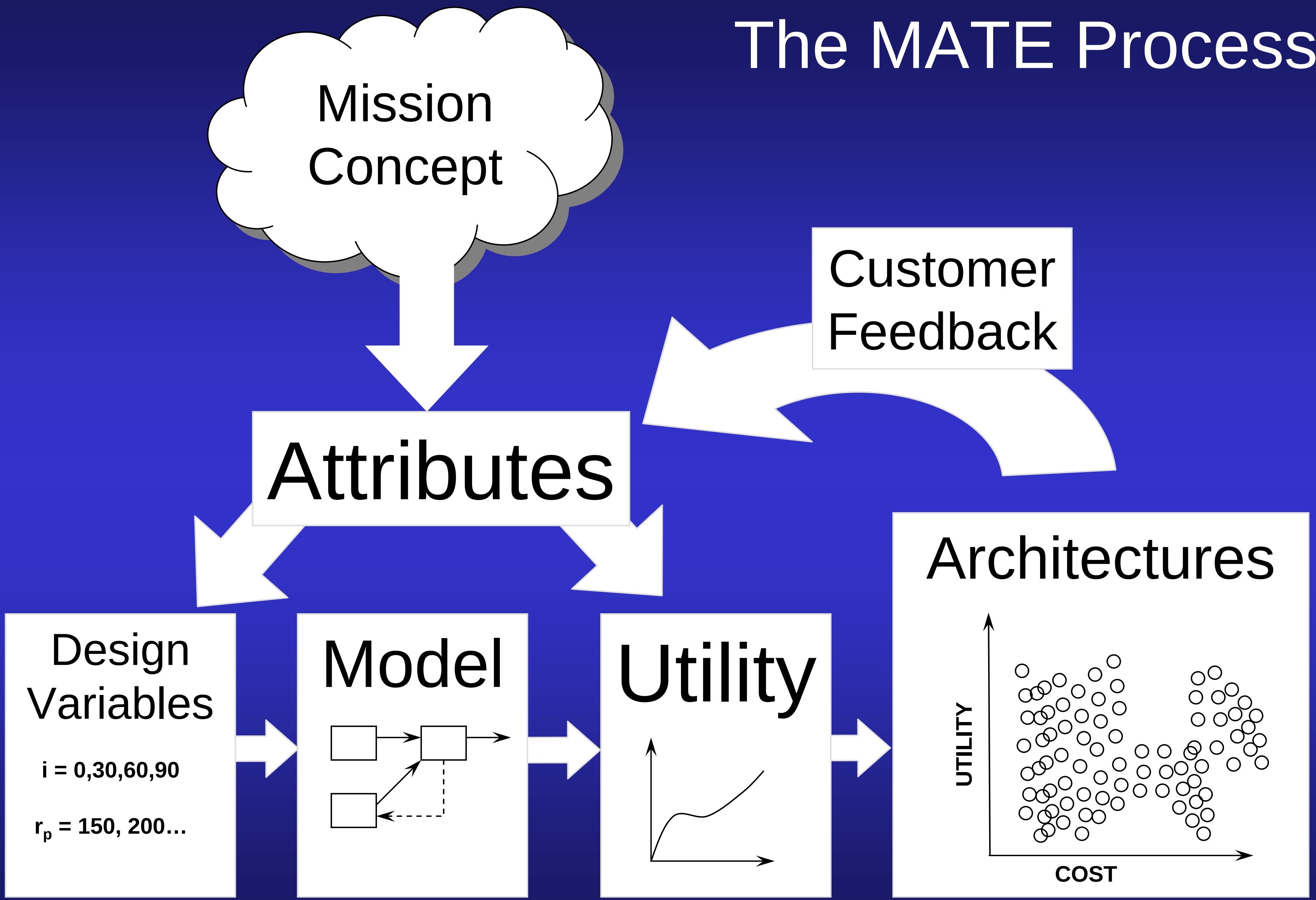
- Example architecture choice

Summary of Key Cost and Utility Drivers

1. Apogee altitude - lifetime driver
2. Perigee altitude - lifetime driver
3. ΔV - lifetime driver

- Power drives cost
- Thruster choice drives cost
- Dry mass drives cost

The MATE Process



MATE Accomplishments

- Ascertained mission parameters
- Explored customer preferences
- Translated attributes into utility functions
- Defined tradespace
- Developed simulation code
- Evaluated thousands of architectures
- Identified optimal architectures

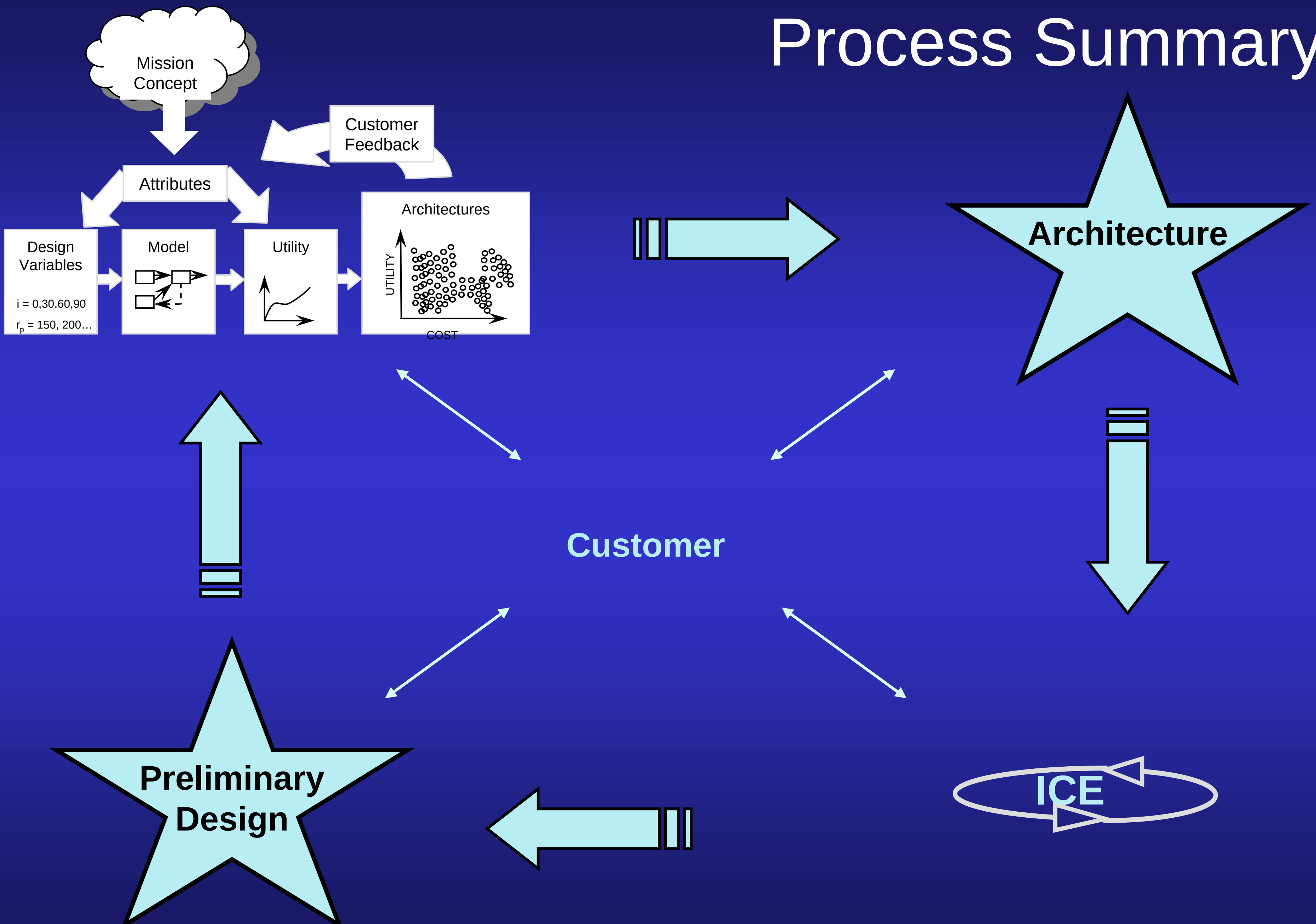
MATE Process Evaluation

- Focus on customer desires and not point solution
- Improved insights into design tradeoffs
  - Some counterintuitive findings
- Ability to expand a single-point attribute into a utility
  - Taking one data point and integrating to find altitude utility

MATE Process Evaluation

- Modeling constraints prevent full exploration of the tradespace
- Clear understanding and facilitation are keys to a successful implementation of the MATE process

Process Summary



MATE-CON

- Overview
  - A process allowing subsystems to trade design parameters in a formal setting
    - Provides real-time feedback into the effect of those trades on:
      - Other subsystems
      - The overall utility of the mission
  - Facilitates detailed analysis of the tradespace
  - Faster than traditional processes

MATE-CON

- Human interaction
  - – All engineers operate within the same environment both physically and technically
    - Human interaction key to process
    - Design sessions "scripted" and controlled by one person
    - Many eyes on final product
  - – Experts in each area design key trades which directly affect their subsystem
    - Examine all major spacecraft subsystems
    - "Father knows best"

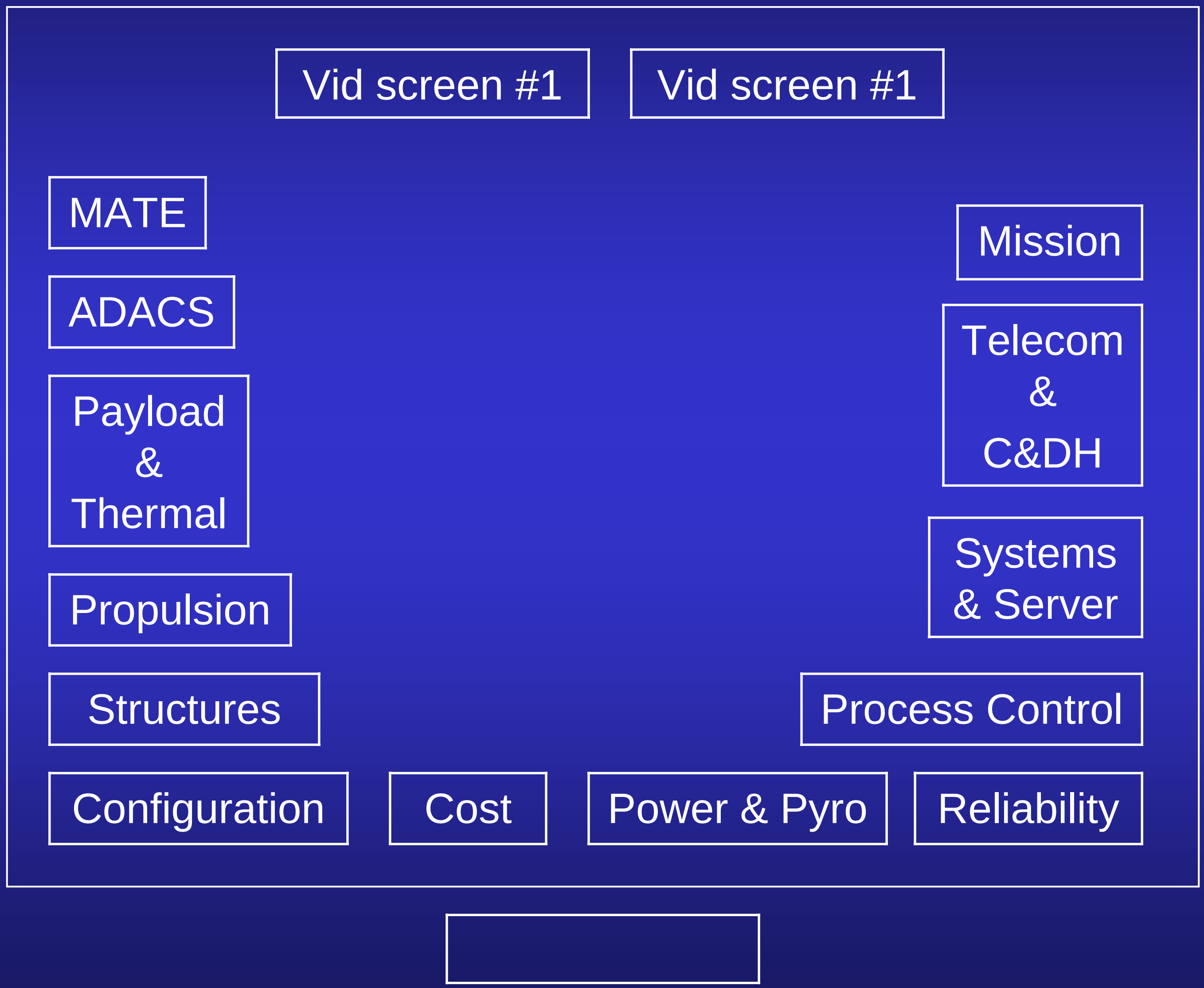
MATE-CON

- Spacecraft subsystems modules
  - – Design and programmatic level
  - – ICEMaker software tool
    - Interdependent Microsoft Excel Workbooks
    - Common server
  - – Matlab integration allows for link to utility trade in first half of class
  - – Design convergence
  - – Subsystem tradable parameters
    - Trade trees

MATE-CON

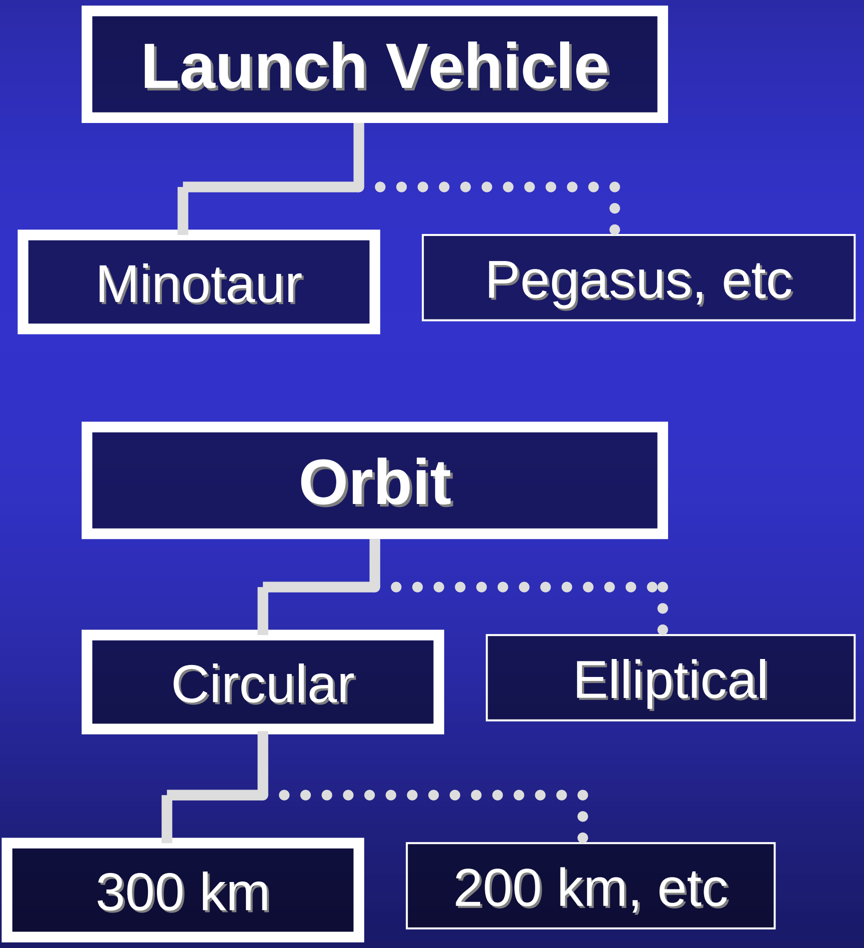
- Mapping a converged design to utility
  - Multi-step process
  - Design to an architecture with an *a priori* utility value
  - Subsystem trades
  - Propagate traded parameters through worksheets
    - Design Convergence
  - Re-calculate utility value

ICE Setup


Vid screen #1
Vid screen #1
MATE
ADACS
Payload & Thermal
Propulsion
Structures
Configuration
Cost
Power & Pyro
Reliability
Process Control
Systems & Server
Telecom & C&DH
Mission

Mission

- The "primary" subsystem
  - Contains key design variables
    - Orbit parameters
    - Total delta V for the mission
- Major components:
  - Orbit determination
    - Includes maneuvers for insertion and deorbit
  - Launch vehicle selection
    - From database of small/medium US launch vehicles
  - Lifetime calculation
  - Delta V budget

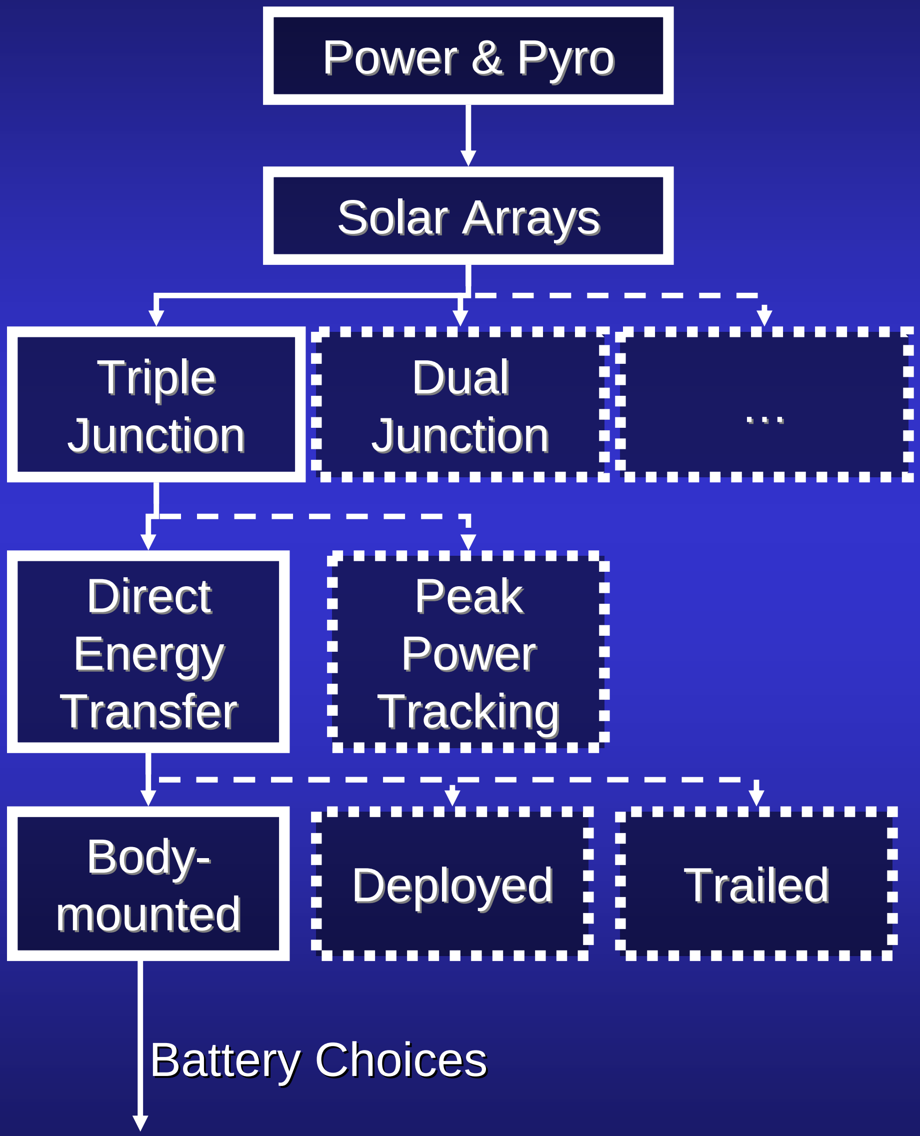


Payload & Thermal

- Payload
  - 3 Payload components
    - Satellite Electrostatic Triaxial Accelerometer (SETA)
    - Absolute Density Mass Spectrometer (ADMS)
    - Composition and Density Sensor (CADS)
  - Mass: 20.5 kg
  - Power: 48 W

- Thermal
  - Took in temp. constraints
  - Used a spherical model
  - Two possible surfaces
    - 1st surface = solar panels
    - 2nd surface chosen from list
  - 2nd chosen to ensure thermal balance in two extreme scenarios
  - Dynamic calc validated balance
  - Insulation mass calculated for fuel tanks, lines
  - Mass: 2.249 kg
  - Design quickly converged on passive control

Power and Pyrotechnic

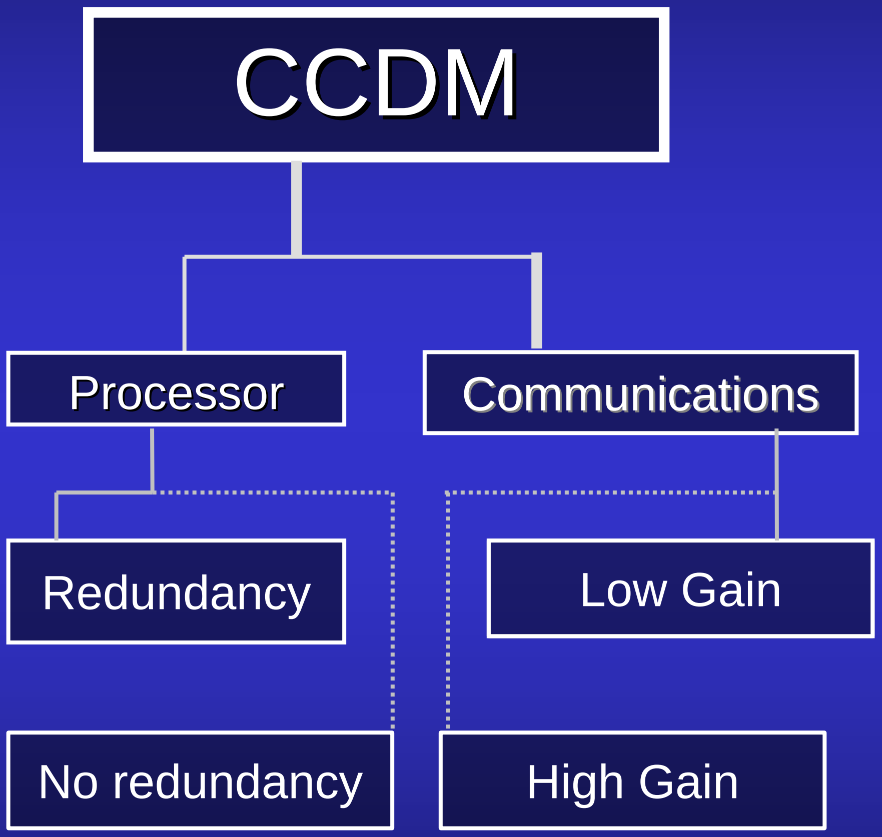


- Calculates power requirements for all modes
- Selects / sizes solar arrays
- Selects / sizes batteries
- Estimates mass of power subsystem

- Power requirements quickly drove power subsystem to body-mounted high efficiency solar arrays
  - Less contingency

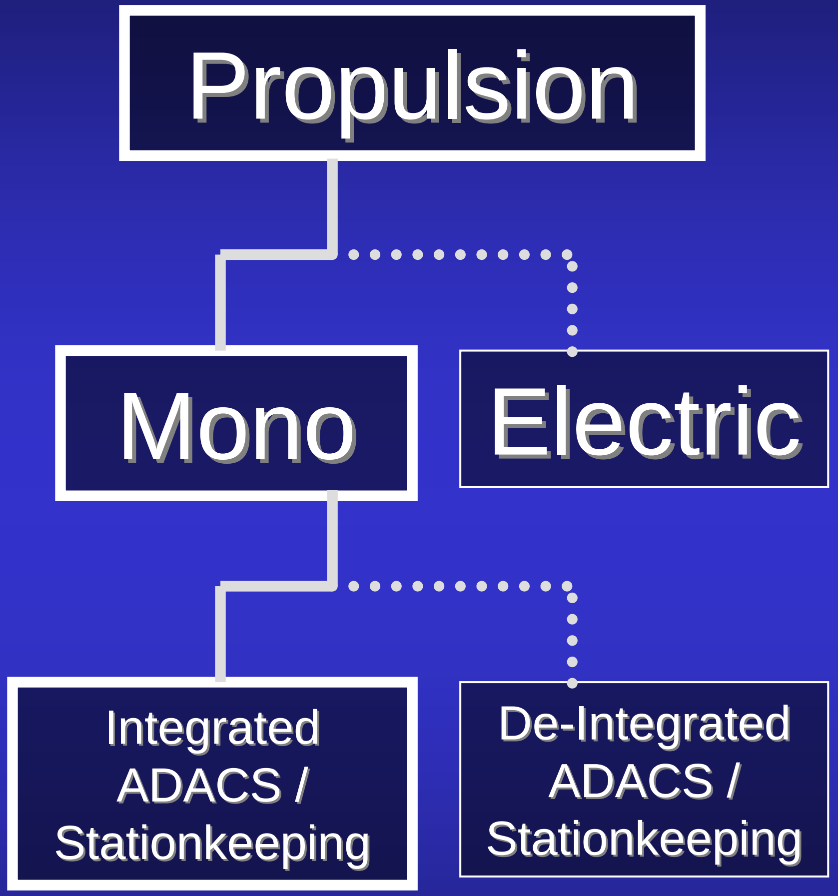
Command Control And Data Management (CCDM)

- 3 on Board computers
  - 2 for redundancy
  - 1 for safe mode handling
- High speed bus
- (2) 20 Gbit recorders
- 2 Low gain antennae
  - Conical Log-Spiral
- 2 sets transceiver / ampilifier system (with all associated hardware)



Propulsion

- ADACS *and* station keeping thrusters integrated
  - – Electric propulsion eliminated due to power
  - – 5 N Monopropellant (Hydrazine) thrusters
    - Simple blowdown system
    - Proven, available
    - Cheap
- I_{sp} choice determines total mass of fuel for required Delta-V



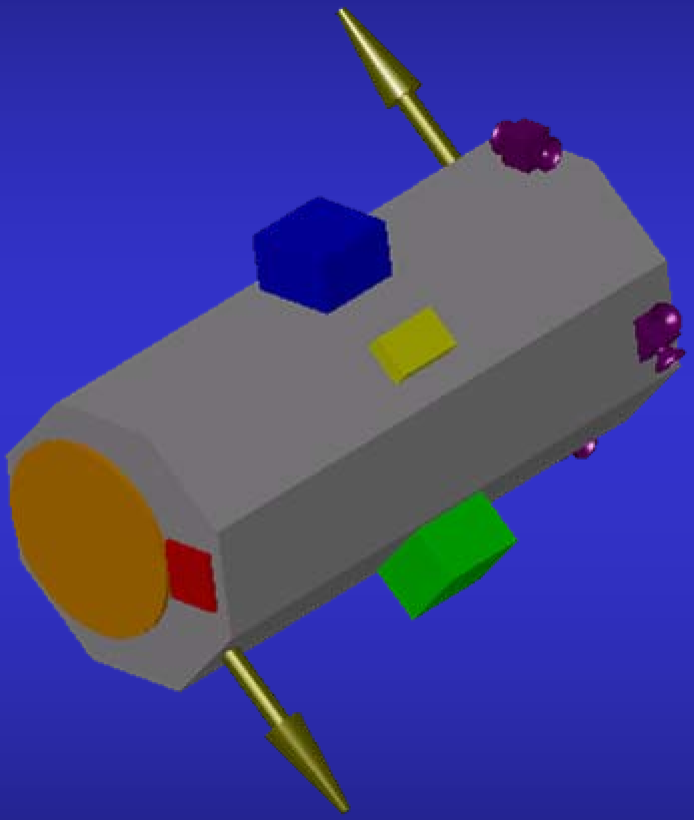
Structures & ADACS

- Structures
  - Structural mass
    - Primary
    - Secondary
    - Miscellaneous
  - Launch loads
    - Acoustic
    - Random shock and vibration
  - Mechanism selection
    - Requirement / need
    - Power

- ADACS
  - Disturbances
    - Aerodynamic *(eliminated by the assumption of C.G. ahead of C. of pressure)*
    - Gravity gradient
    - Solar pressure
  - Pointing requirements from Payload and Com: 0.1 degree
  - Sensors
    - 1 GPS
    - 2 Horizon sensors

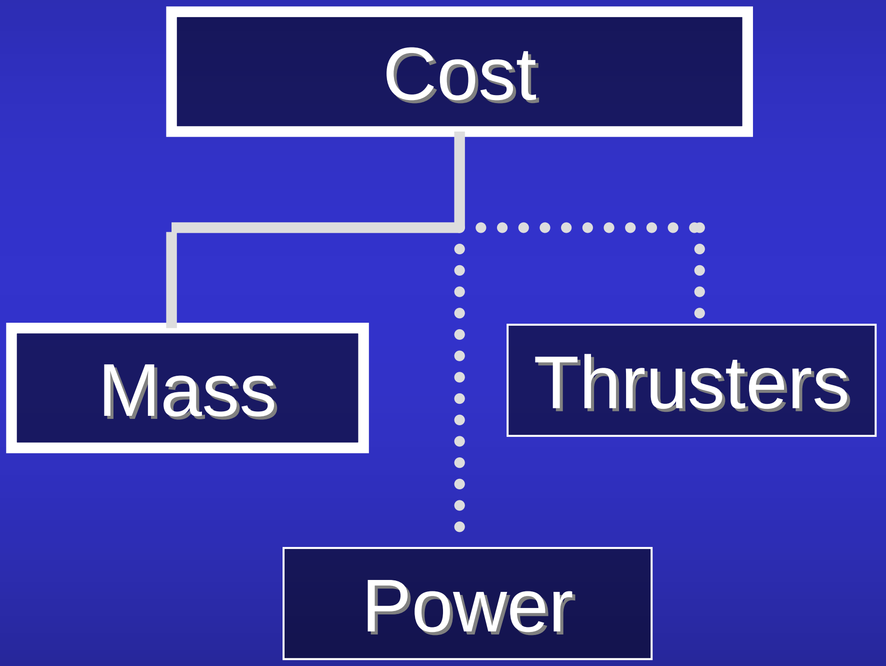
Configuration

- Arranges subsystem components
  - DrawCraft
  - SolidWorks
- Generates weight distribution, physical characteristics
- Parameters can be changed dynamically
- Human-in-the-loop required
- Sensors are ram-facing
- Center of gravity is forward of half-chord



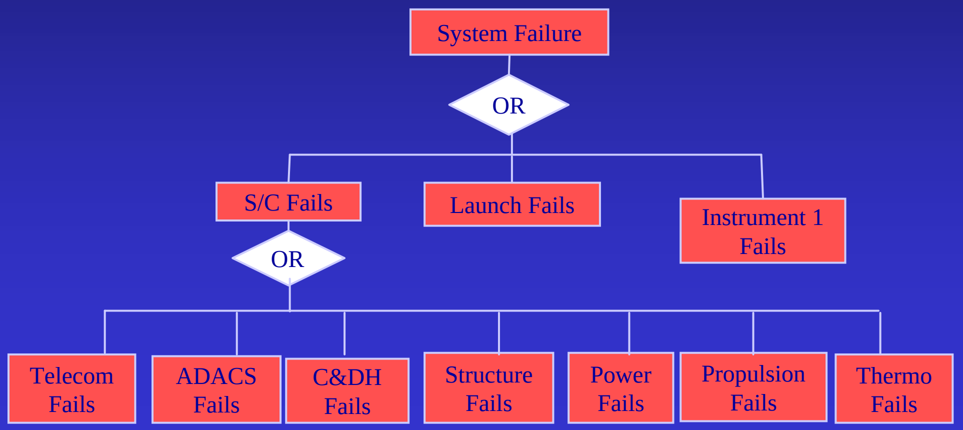
Cost

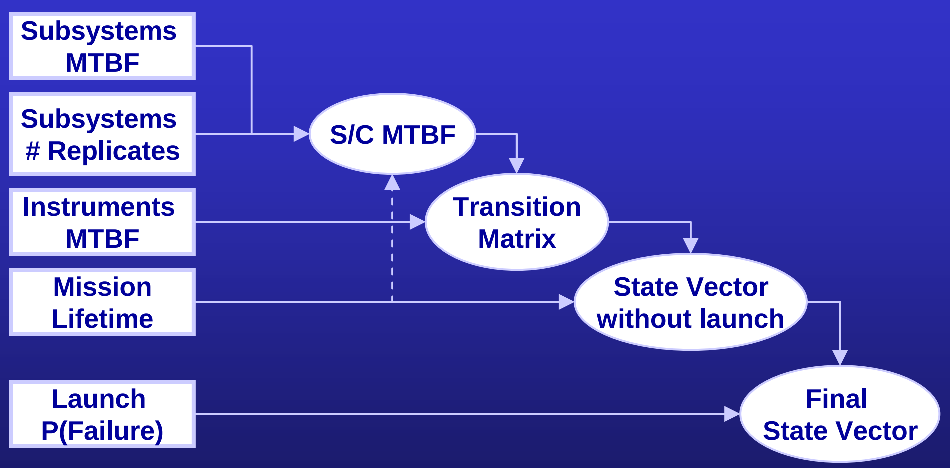
- 2 Models
  - SMAD CER
  - SSCM (small sat. CER)
  - Compared to Aerospace Corp's model for Small Sats
    - Same order of magnitude
    - 20 ~ 30% less than SMAD



Reliability

- Uses Markov Modeling to calculate reliability at mission lifetime
- Four possible states: full functionality, instrument 2 or 3 fails, instruments 2 *and* 3 fail, system failure
- Fidelity suffered from lack of knowledge of true Mean Times between Failures



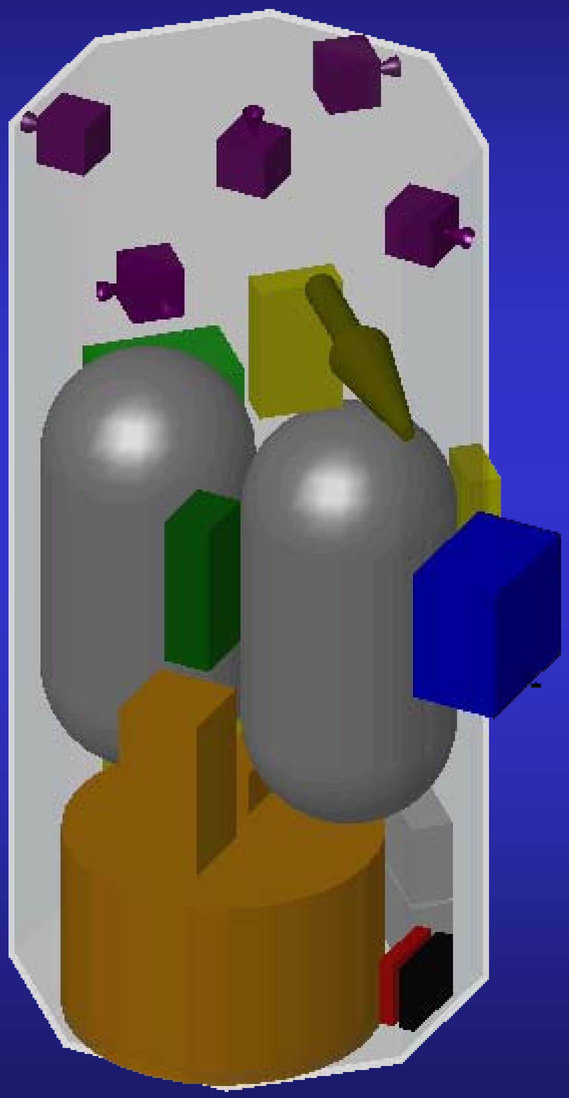


MATE-CON Chair

- X-TOS is first use of MATE-CON Chair
- Purpose
  - Represents the customer via his/her expressed preferences (utility curves)
  - Sets goals and guides concurrent design process to maximized value for customer
- Features
  - Excel interface to concurrent engineering suite
  - MATLAB back-end for attribute and utility computations
  - MATLAB can be used to generate additional design roadmaps

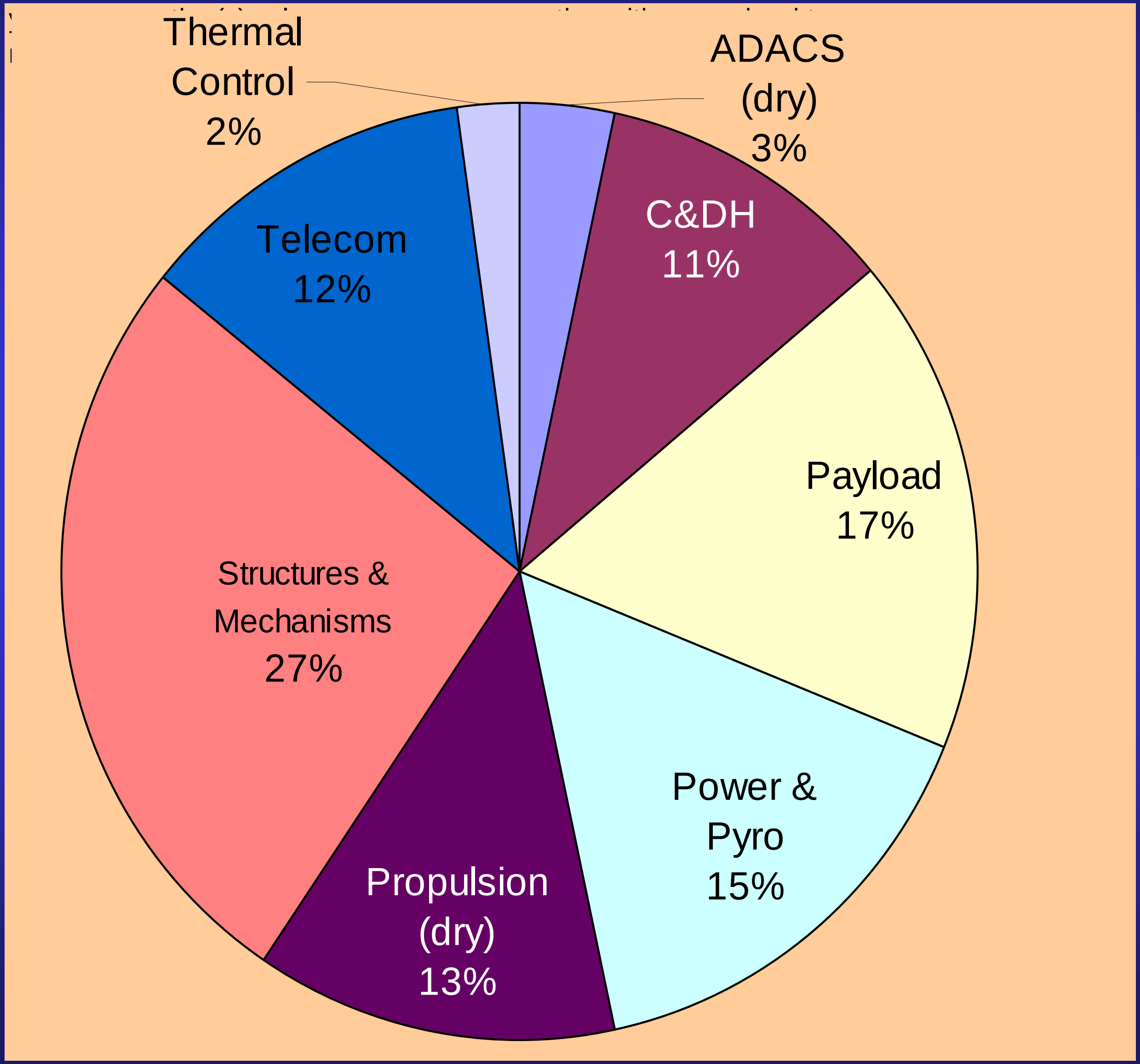
Baseline X-TOS Design

- Est. Cost: $71.7 M
- Utility*: 0.705
- Wet Mass: 449.6 kg
- Dry Mass: 188.9 kg
- Lifetime: 0.534 years
- Orbit: 185 km circular
- LV: Minotaur

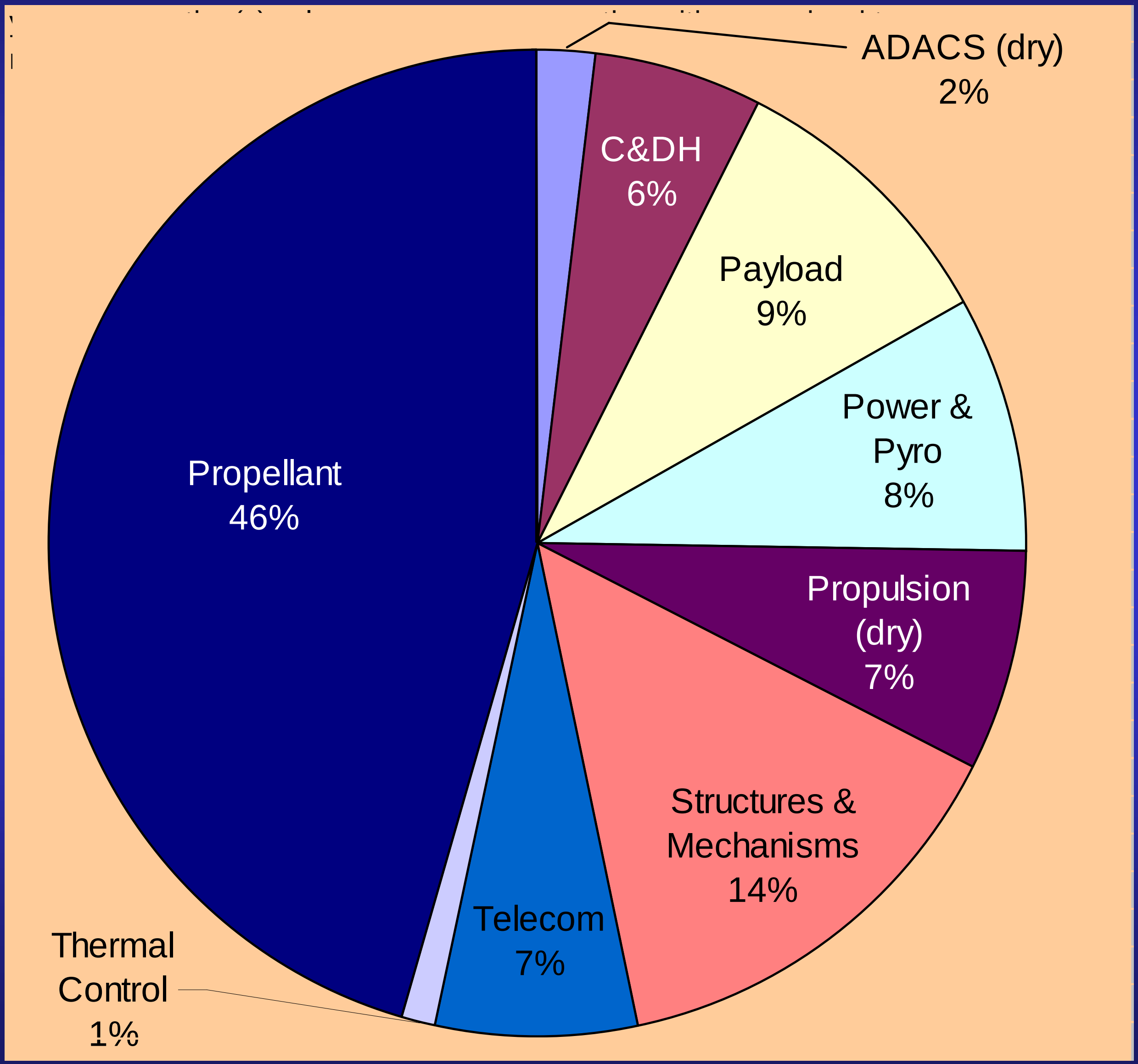


* Denotes "Original" User Utility

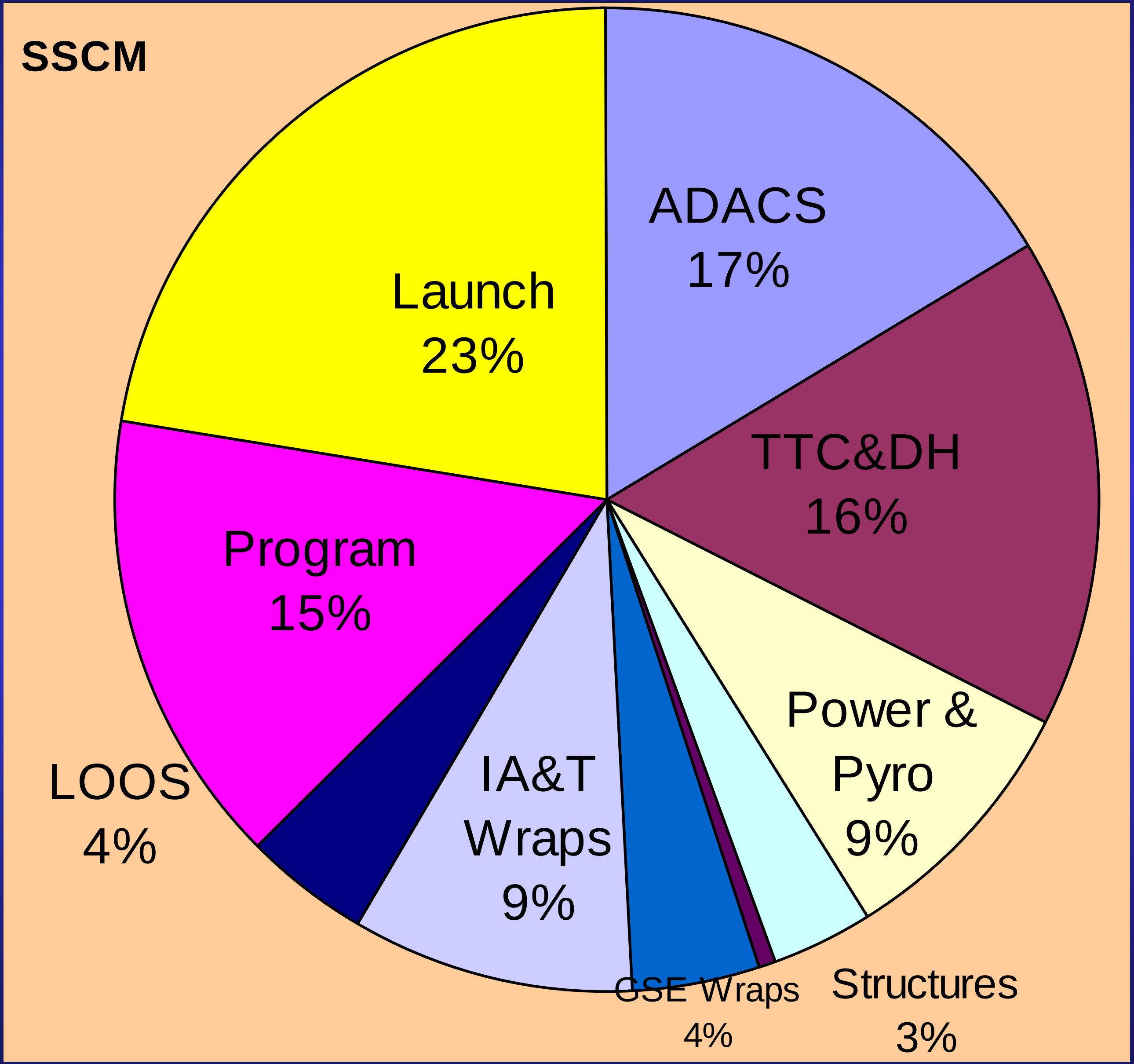
Dry Mass Breakdown Chart



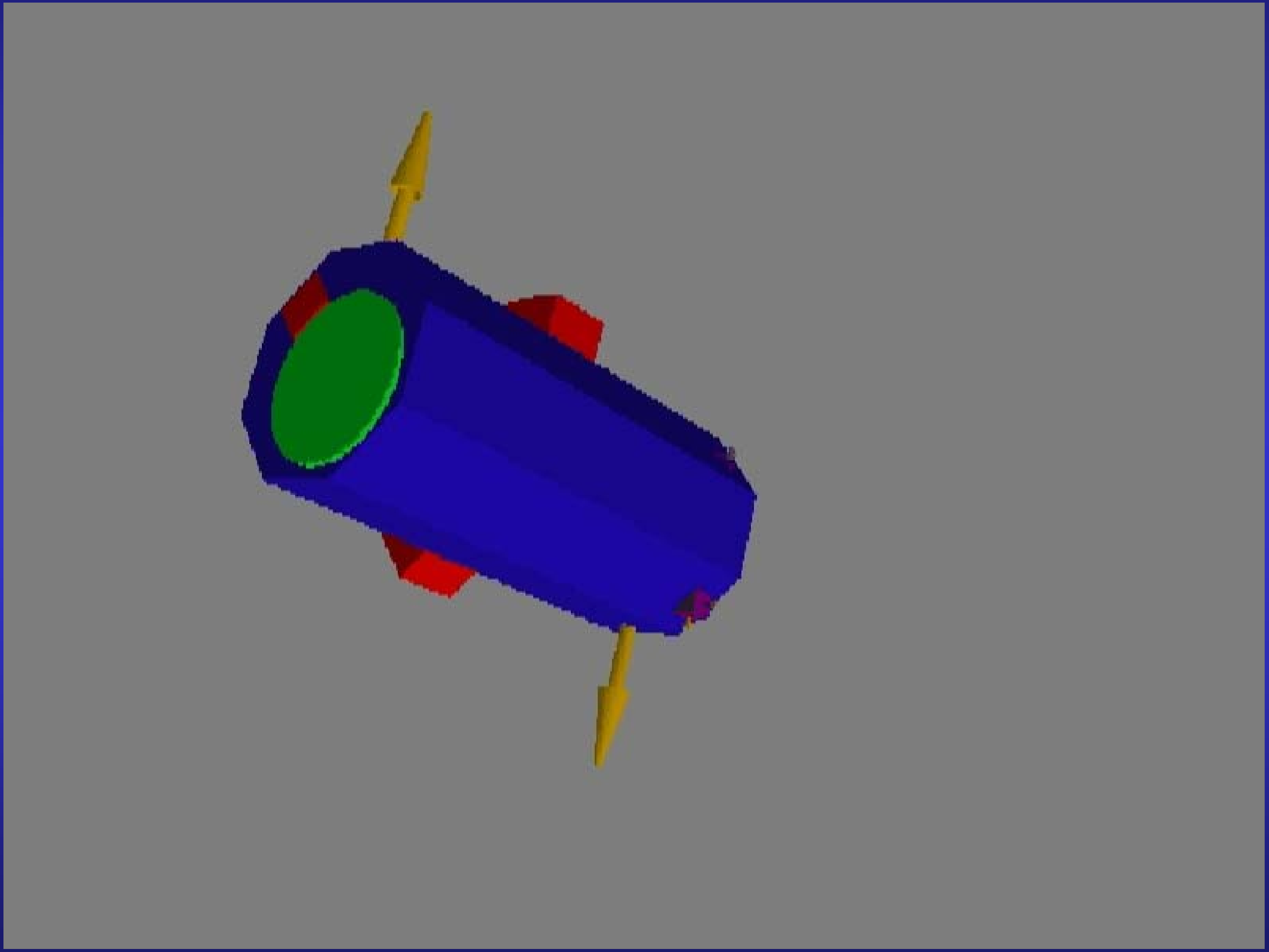
Wet Mass Breakdown Chart



SSCM Breakdown Chart



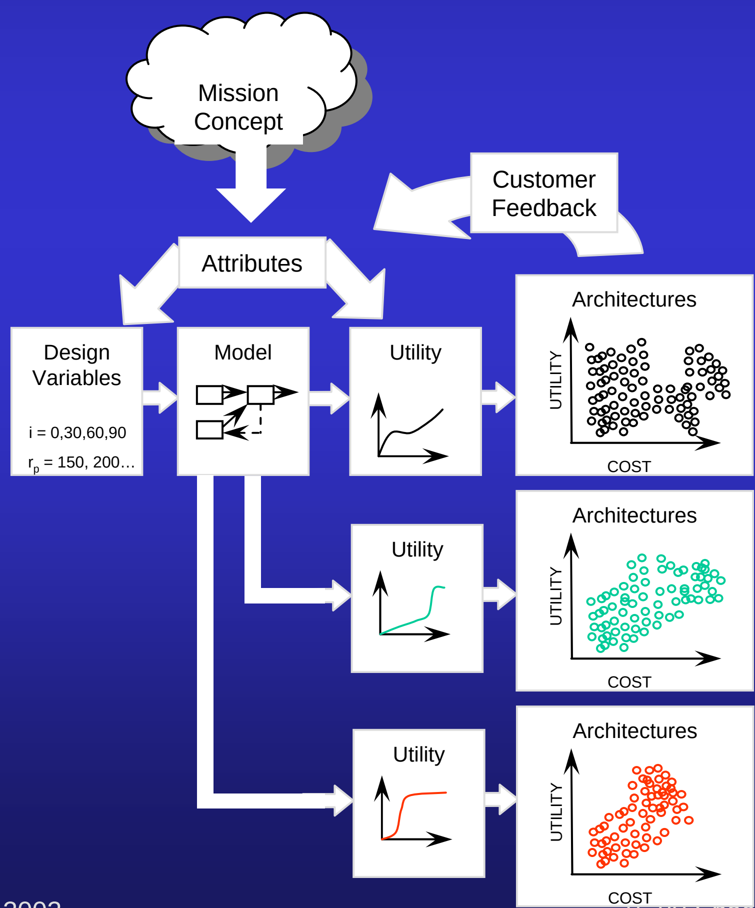
Configuration



Uncertainty and sensitivity analysis

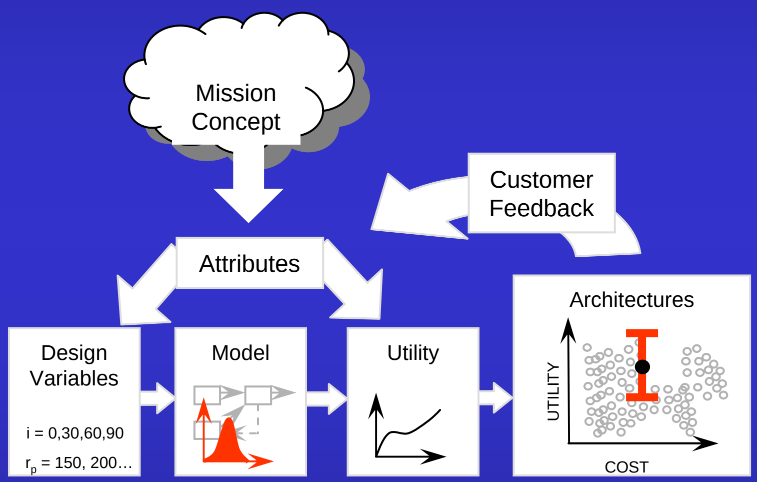
Preference Uncertainty

Rearrangement of architectures in *different* tradespaces

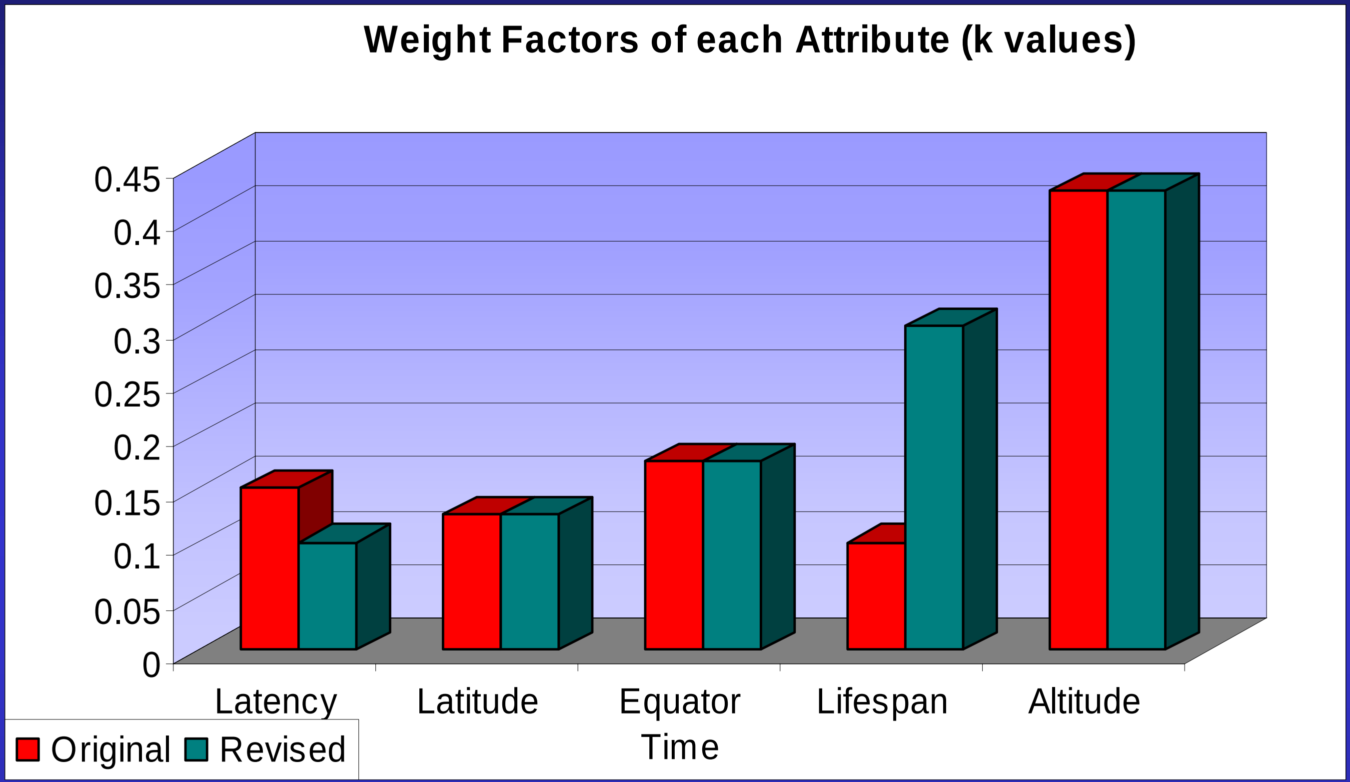


Model Uncertainty

Variation in *same* space tradespace



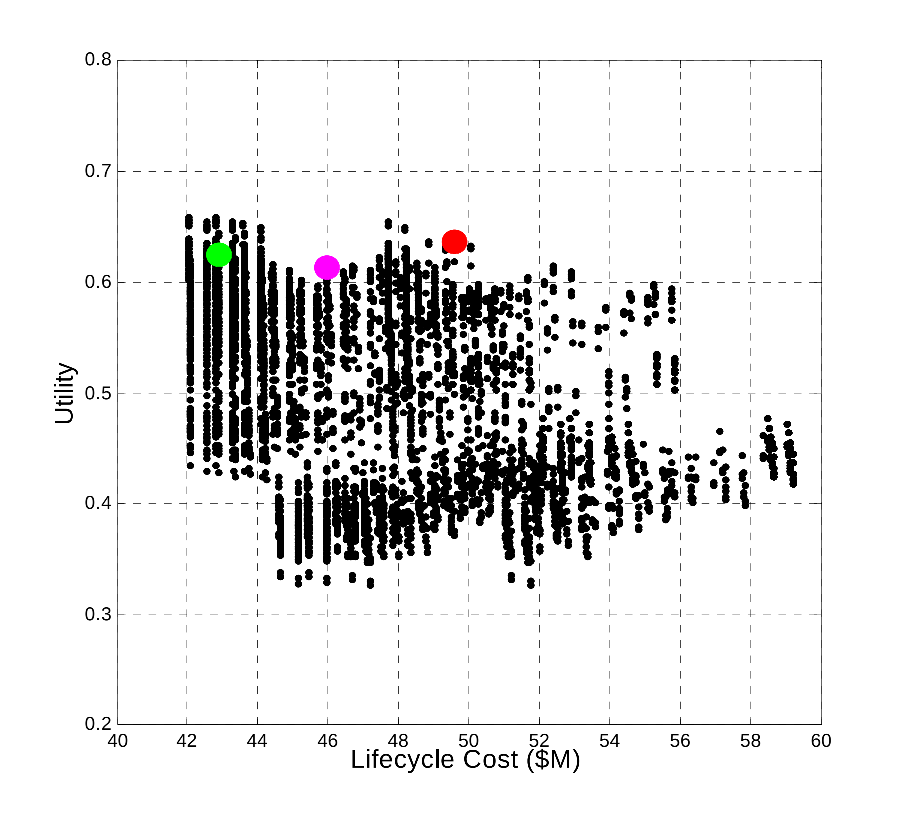
Changing User Preferences (I)



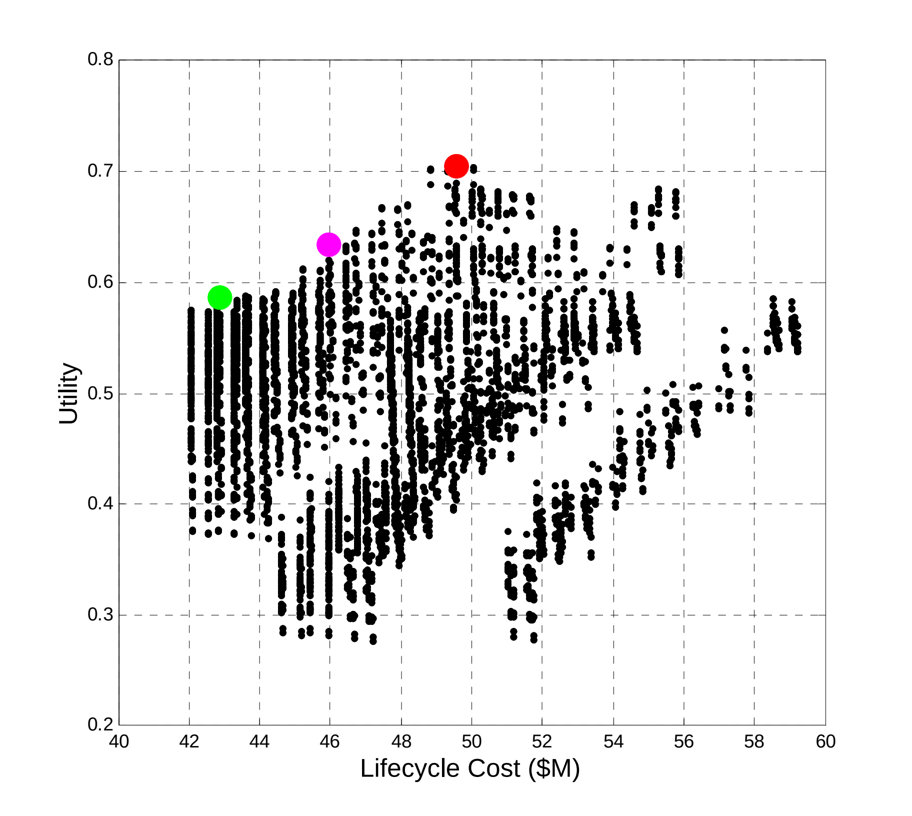
- After reviewing MATE results, user expressed revised preferences
- Increased importance of Lifespan
- Slight decrease in importance of Latency

Changing User Preferences (II)

Original



Revised



- A change in user preferences may move architectures away from or on to the pareto optimal front

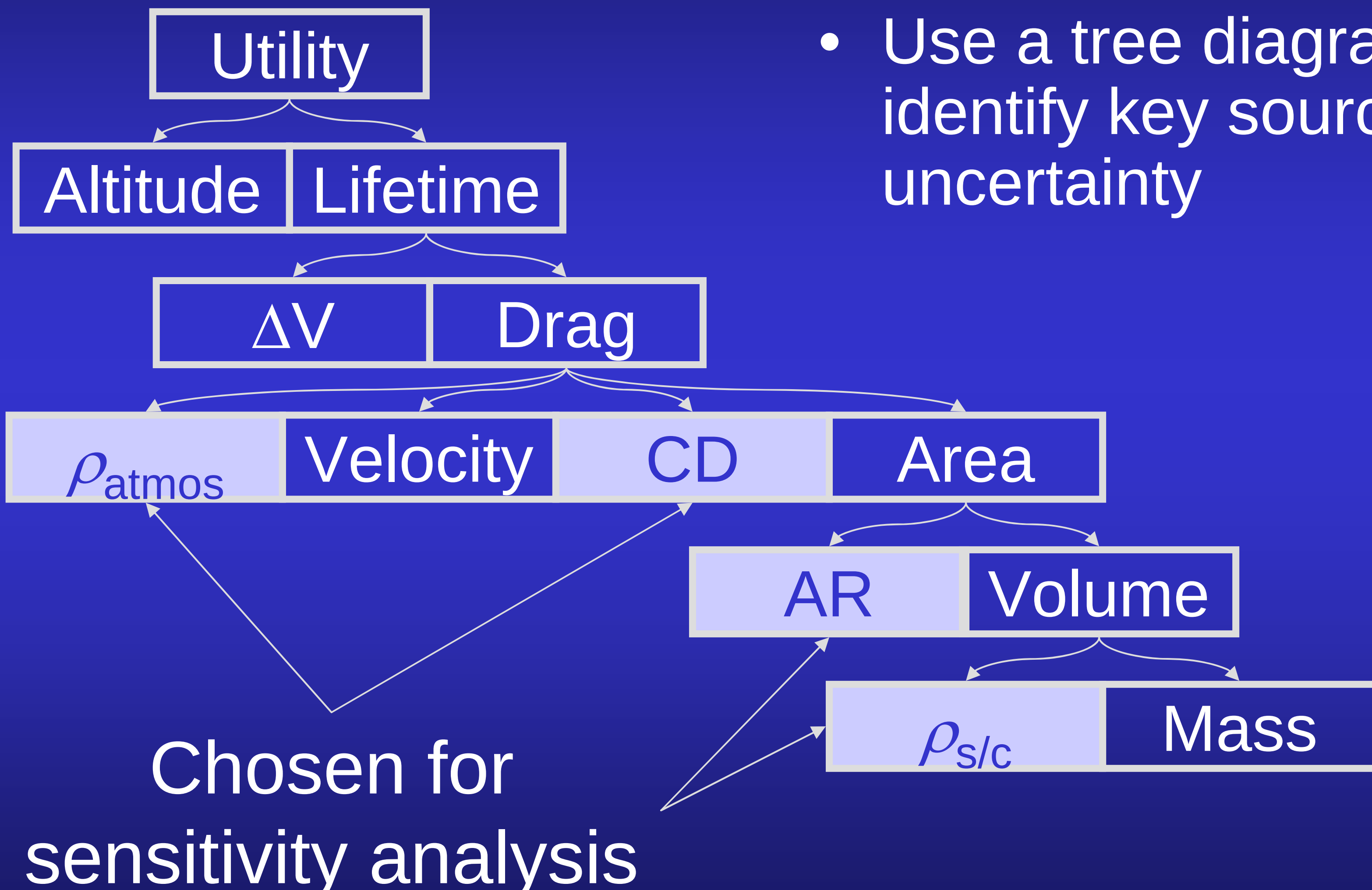
Changing User Preferences (III)

- New preferences lead to changes in objectives for preliminary detailed design

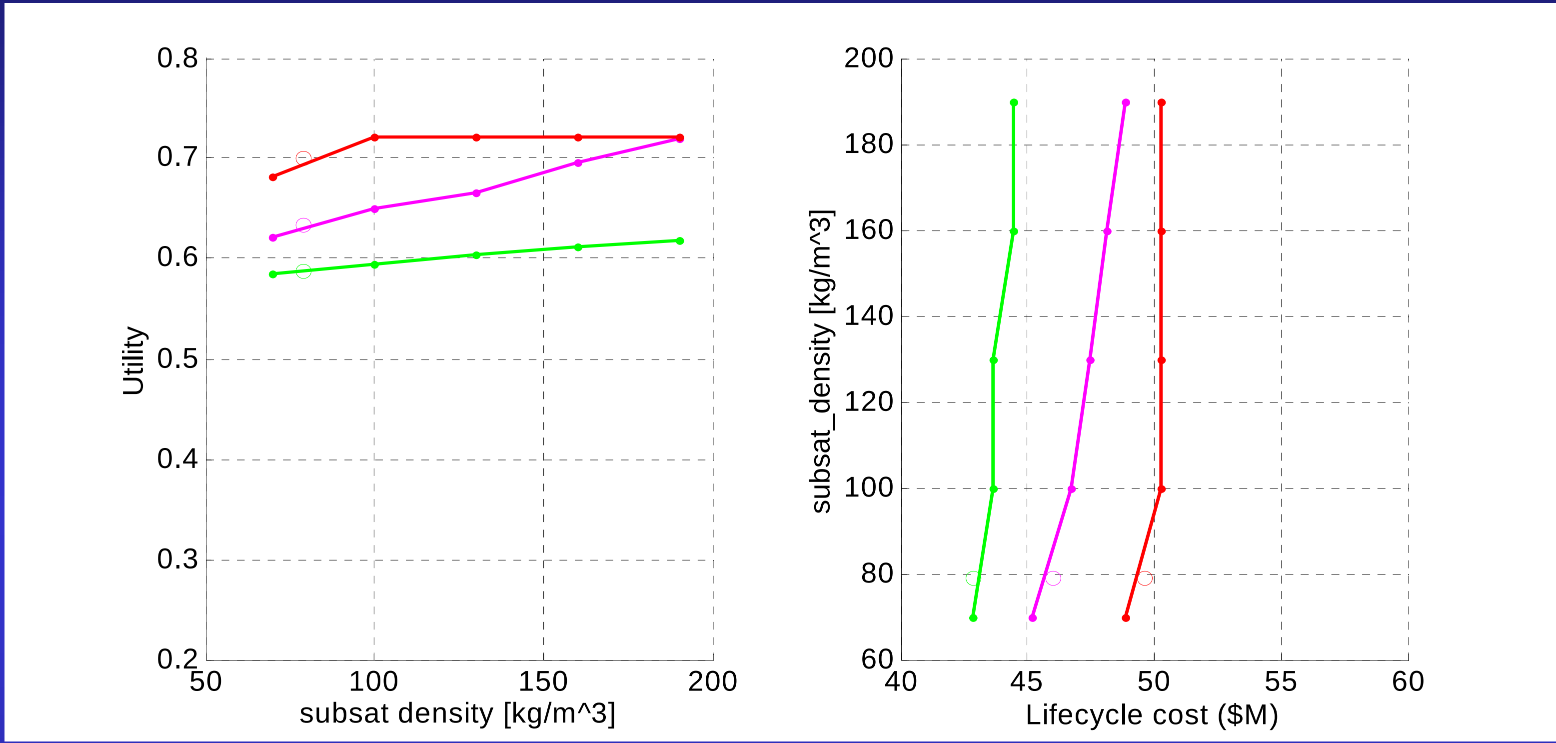
	Mass (wet) [kg]	Pwr (avg) [W]	ΔV [m/s]	Apogee [km]	Perigee [km]	Life [yrs]	Utility (Orig)	Utility (Rev)	Life Cost [$M]
Original Base			1000	250	200	0.75	0.66		
ICE Result	449.6	164	1250	185	185	0.53	0.70	0.61	71.74
Revised Base			1000	350	350	9.8		0.70	
Current ICE	324.3	164	1000	300	300	2.20	0.59	0.55	75.01

Parametric Uncertainty Sources

- Use a tree diagram to identify key sources of uncertainty



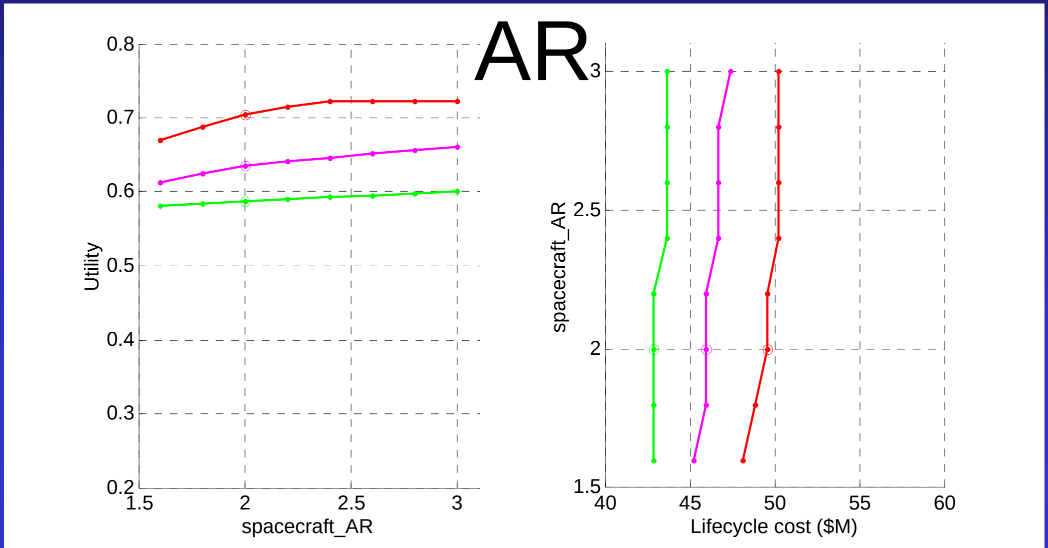
Sensitivity to Satellite Density



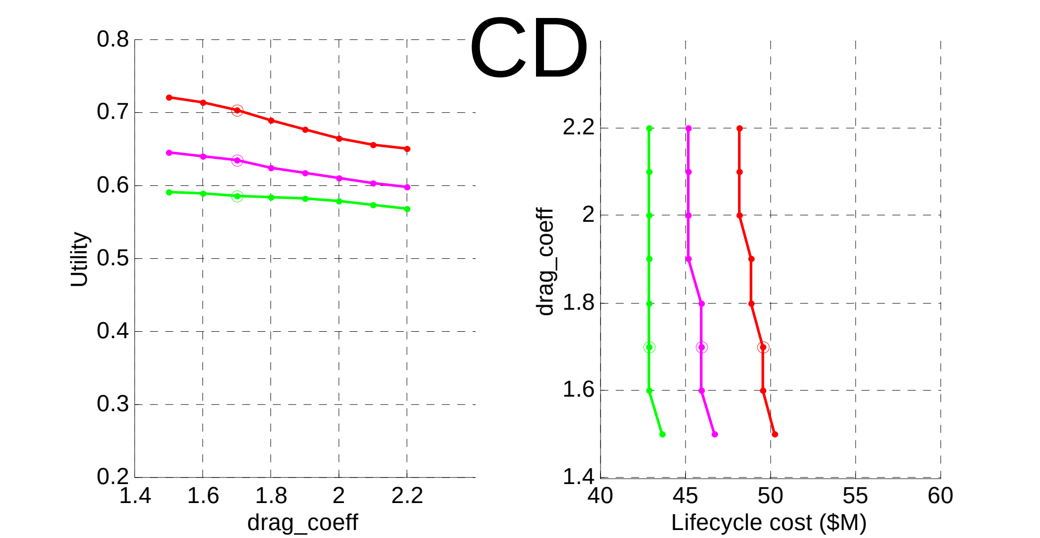
- Magenta has greater sensitivity to $\rho_{s/c}$ than Red or Green
- Red reaches the maximum life of 11 years and no longer benefits from increase in $\rho_{s/c}$ (initially Red has greater slope)
- Green's utility does not depend upon life as much as Magenta

Sensitivity to AR and CD

- Same trend as $\rho_{s/c}$

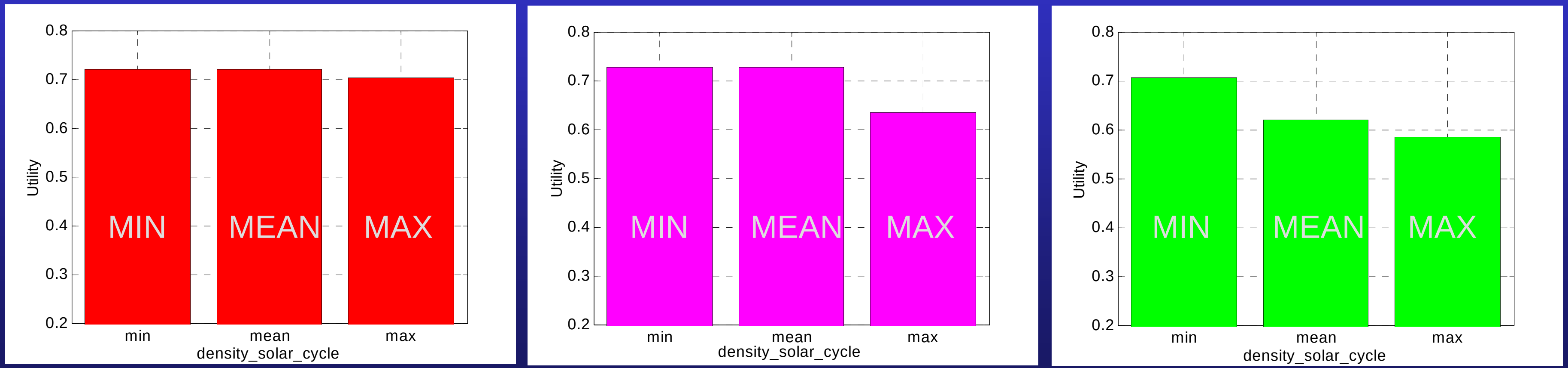


- Lifetime decreases as CD increase
  - Note the non-linear relationship
  - Arises from non-linear utility function for lifetime

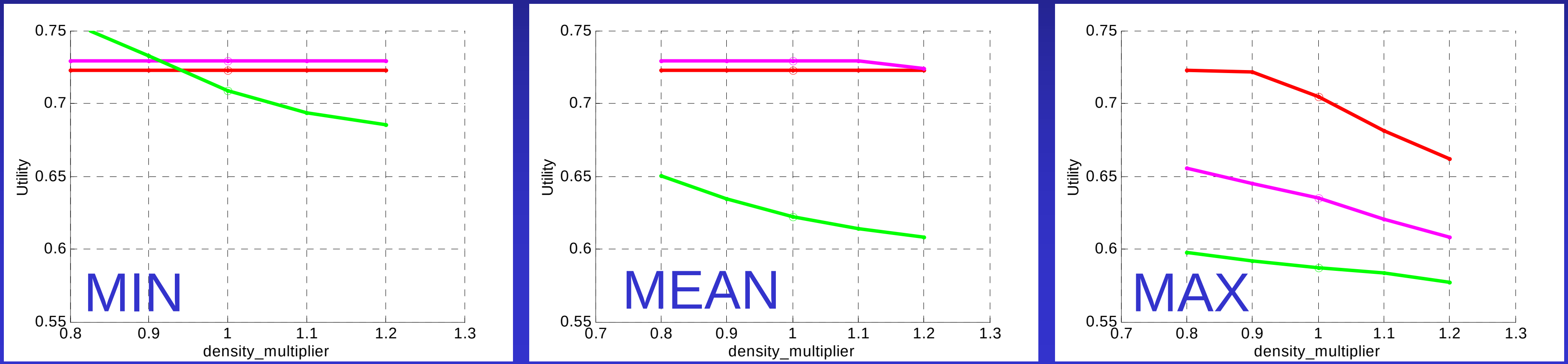


Sensitivity to atmospheric density: Variation caused by the solar cycle

- Note that base case was solar max; Solar cycle state assumed constant throughout life
- Solar cycle has greatest impact on Green
  - Green has lower orbit than Red or Magenta
- At solar min and mean, Magenta has higher utility than Red
  - Density is low enough that Magenta can take advantage of its lower orbit



Sensitivity to Atmospheric Density: Uncertainty in density models



- At solar min Green surpasses both Magenta and Red; while at solar max Green quite low
- The purpose of this mission is to determine the density
  - This is a key unknown that has a large impact on architecture selection

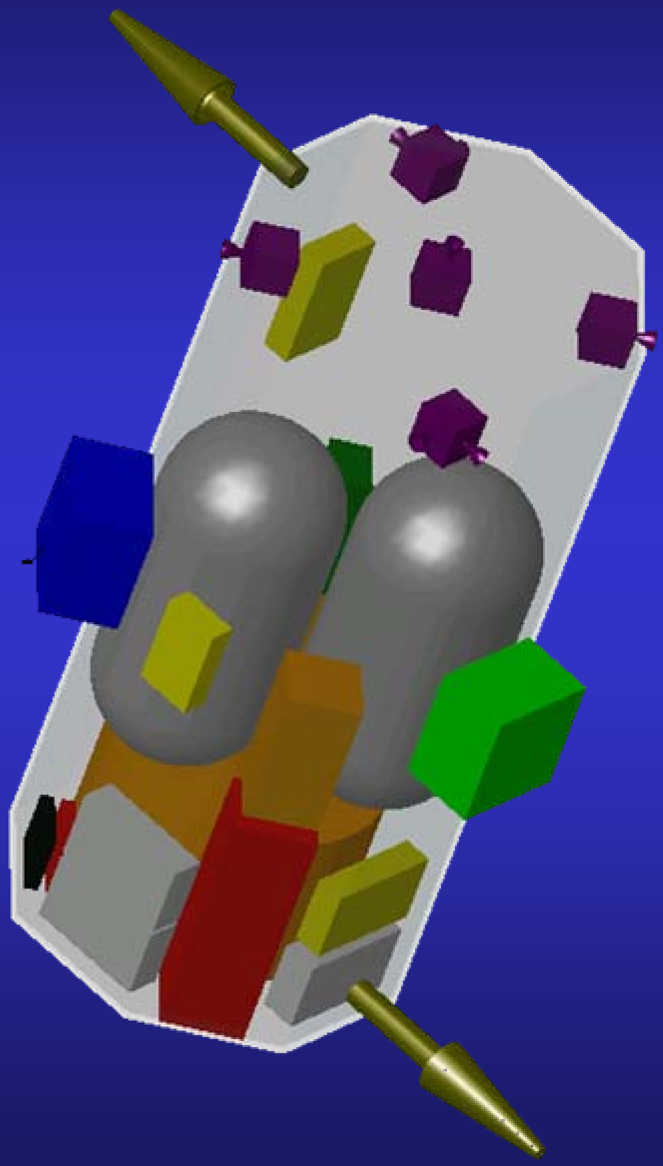
Sensitivity to Atmospheric Density: Dynamically change orbit

- Density is a key driver of utility
- Its value is uncertain
  - Uncertainty of launch date leads to uncertainty of location in solar cycle
  - Current atmospheric model have large errors

> Design spacecraft to have enough fuel and thrust to dynamically change its orbit in response to current atmospheric conditions as mission progresses

Final X-TOS Design

- Est. Cost: $75.0 M
- Utility**: 0.556
- Wet Mass: 324.3 kg
- Dry Mass: 205.5 kg
- Lifetime: 2.204 years
- Orbit: 300 km circular
- LV: Minotaur

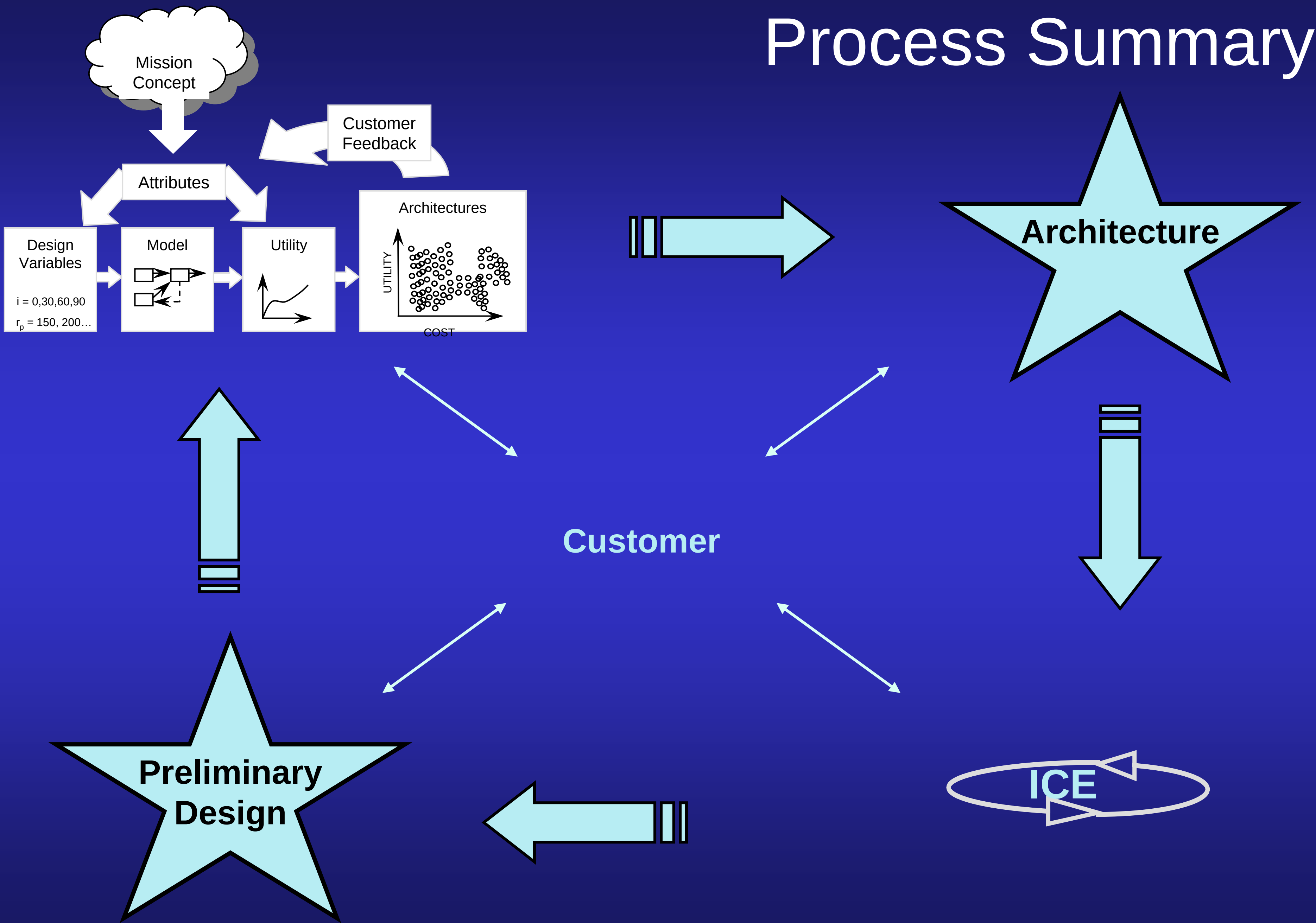


** Denotes "Revised" User Utility

Requirements

- Provide a basis on which to design and test a spacecraft system
  - Lay out specific traits which the system must exhibit
- MATE-CON requirements derived differently than traditional systems
  - MATE-CON trades design vector and attributes to achieve highest utility mission
  - Map design vector and attributes to actual values used for requirements
  - The mission will be in circular low earth polar orbit. The apogee and perigee will be at 300 Km altitude.

Process Summary



MATE-CON Accomplishments

- Stakeholder preferences captured using MAU
- Thousands of architectures traded based on design vector and mission scenario
- An architecture and a preliminary design meeting user and customer preferences identified
- Feedback from user incorporated quickly
- Robust, modular, reusable code developed

Completed process for architecture and preliminary Design selection and assessment in 3 months!

Design Insights

- Utility plays a significant role
  - Initial utilities show that S/C design does not matter
    - Orbit is the largest driver
  - Revised utilities show that S/C does matter
- ‘Flying Bomb’
  - Large amounts of fuel can bring down uncertainty and increase robustness
    - Can modify orbit dynamically
  - Can possibly gain significant utility from re-entry

Design Insights (II)

- Atmospheric density has greatest uncertainty
  - We are designing for an unknown environment
    - Need flexibility
- Drag is an enormous driver
  - MATE-CON reveals unintuitive finding

MATE-CON Insights (I)

- Communication is key!
  - Iterate with user/customer
  - Establish contact with user/customer early in the process
  - Facilitate communication within the team
    - Work in the same room!
    - Ensure shared mental model of process, software architecture and information flow
    - Manage coupling and interaction between subsystems

MATE-CON is an inherently human-centered process!

MATE-CON Insights (II)

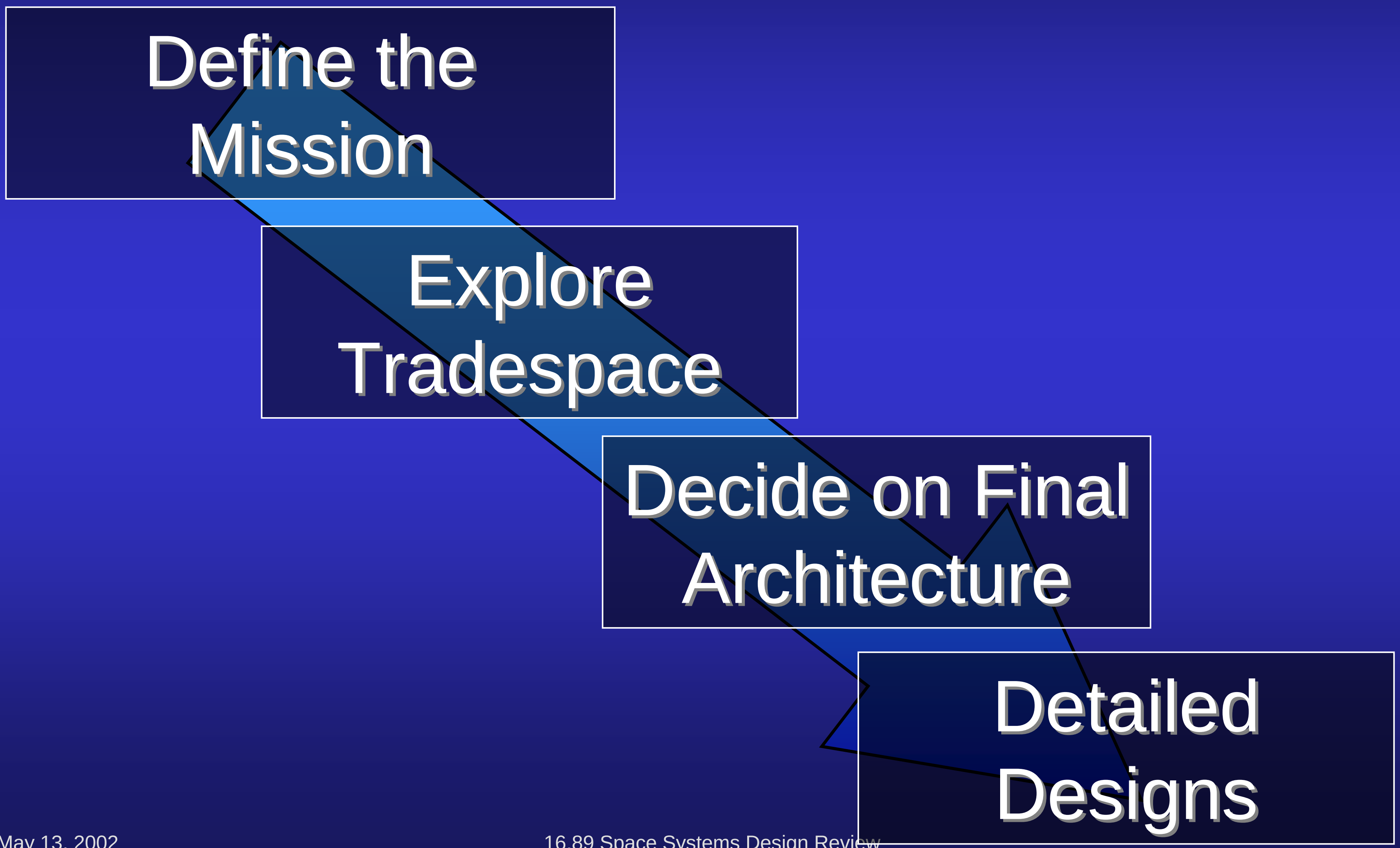
- Availability of past projects facilitates learning, but can be dangerous if used without critical judgment
  - Model reuse can be inefficient or even wrong when the underlying assumptions are different!
- Agility is essential when working under time pressure and in an evolving environment
  - True for both people and process!
  - Example: changes in utility curve
- The level of fidelity should be consistent across the different modules
  - Not always the case that high fidelity is better

Future Opportunities/ Recommendations

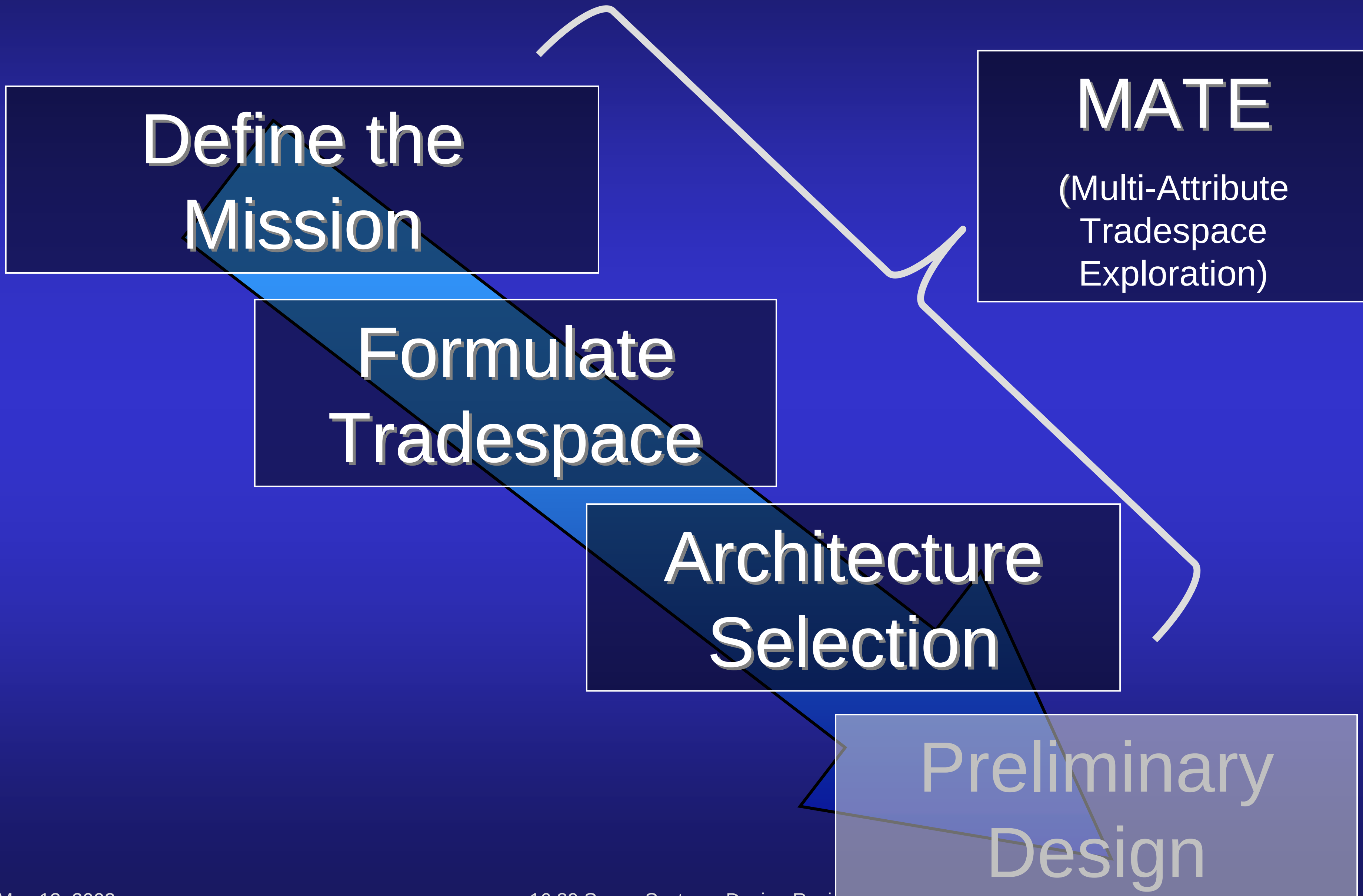
- Assess effect of code reuse on process efficiency
- Increase team-team and team-customer communication in early stages of process
- Improve execution sequencing in ICE
- Facilitate detection of “bugs” in subsystem interactions
- Account for uncertainty
  - Launch opportunity & policy
- Include improved risk assessment
  - Recent work in Portfolio theory

Back-up Slides

16.89 Class Process



16.89 Process



MATE Process Flow

Define the Mission

1. Understand the Mission
2. Create a list of "Attributes"
3. Interview the Customer

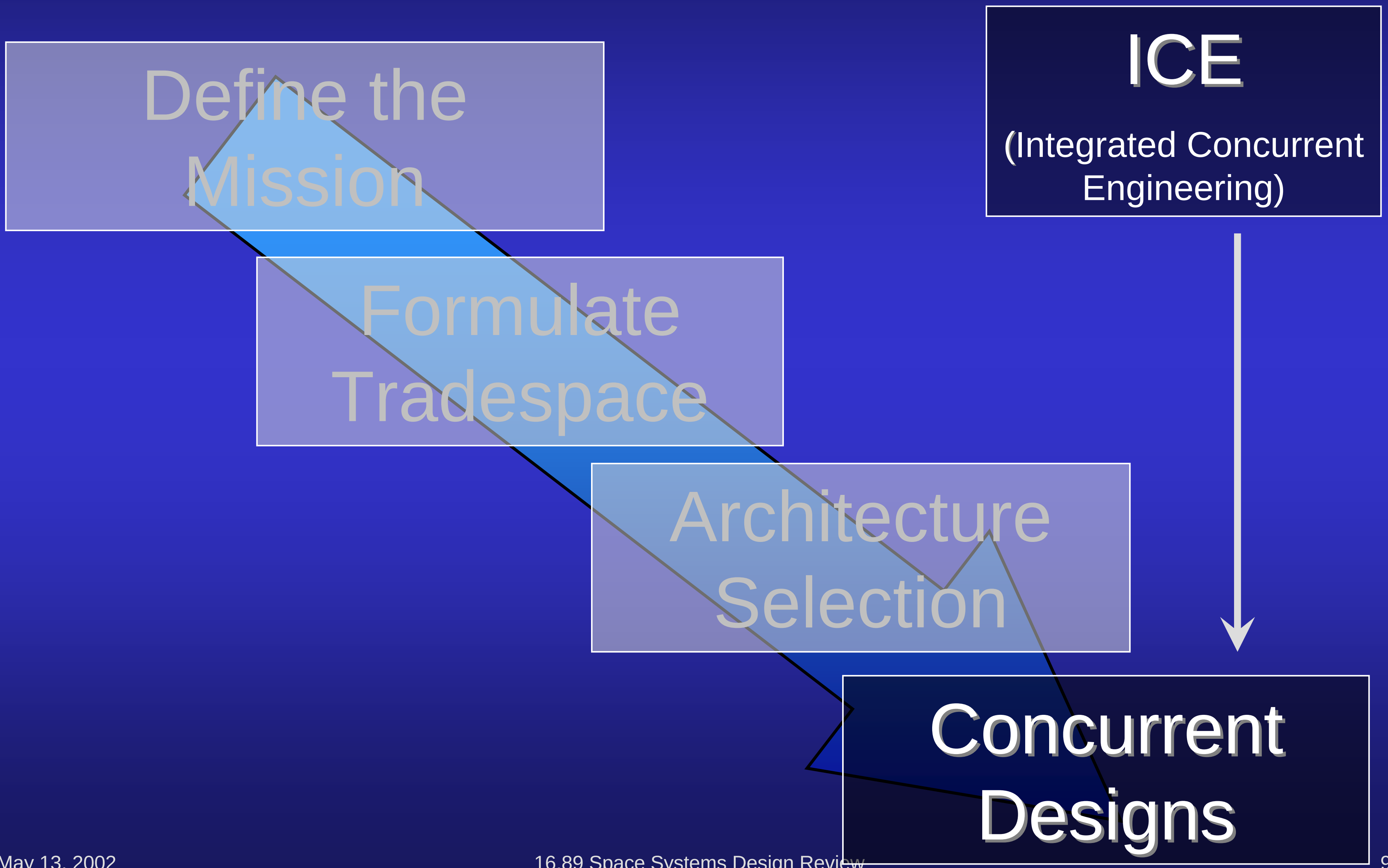
Formulate Tradespace

1. Create Utility Curves
2. Create Design Vector
3. Create Simulation Software

Architecture Selection

1. Find Utilities / Analyze Architectures
2. Examine Utility vs. Lifecycle Cost Plot
3. Select Architecture

16.89 Process Tools



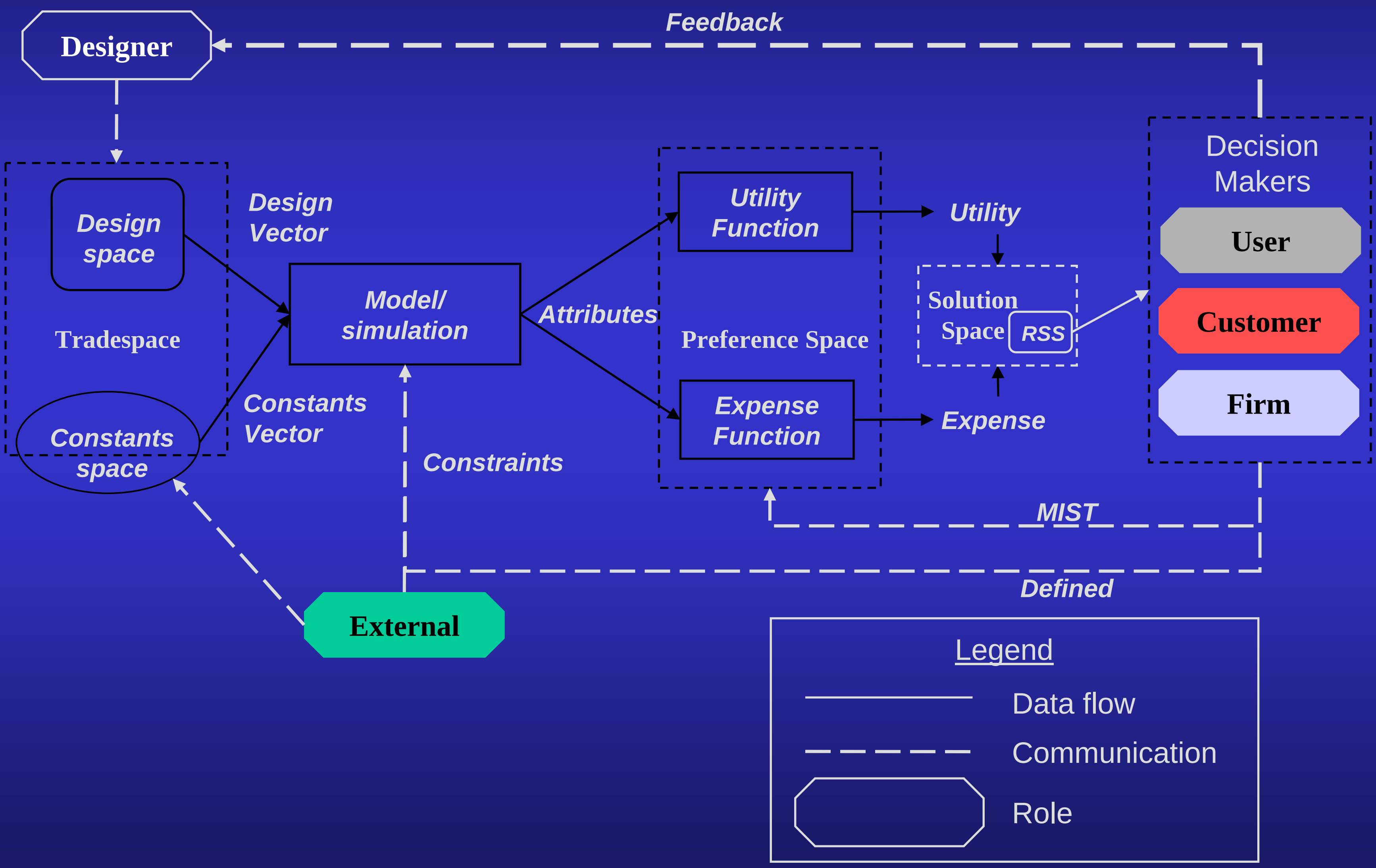
Systems Engineering Tools

- MATE-CON
  - Multi-Attribute Tradespace Exploration with Concurrent Design
- Matlab, STK (Satellite Tool Kit)
- ICE
  - Integrated, Collaborative, Model Based Design

What is MATE-CON?

- A formalized method to explore a design tradespace using model-based simulation
  - Incorporates preferences into decision criteria
  - Based in theory from economics and operations research
  - Multi-Attribute Utility Analysis (MAUA), Cost-Benefit Analysis
- A communication tool to facilitate transfer of wants and needs between designers and decision-makers

MATE



Feedback
Designer
Design space
Design Vector
Tradespace
Constants space
Constants Vector
Model/ simulation
Attributes
Constraints
Utility Function
Preference Space
Expense Function
Utility
Solution Space
RSS
Expense
Decision Makers
User
Customer
Firm
MIST
Defined
External
Legend
Data flow
Communication
Role

MATE Process

- Quantify customer’s preferences in terms of Attributes and Utility functions
- Parametrically model satellite designs using Design Vector
- Simulate various mission scenarios
- Output *thousands* of possible architectures on Utility vs. Cost scale
- Analyze “Pareto-optimal” designs with customer
- Proceed to detail design of selected architecture(s)
- NEED PICTURES ABOVE EACH POINT??

Design Vector

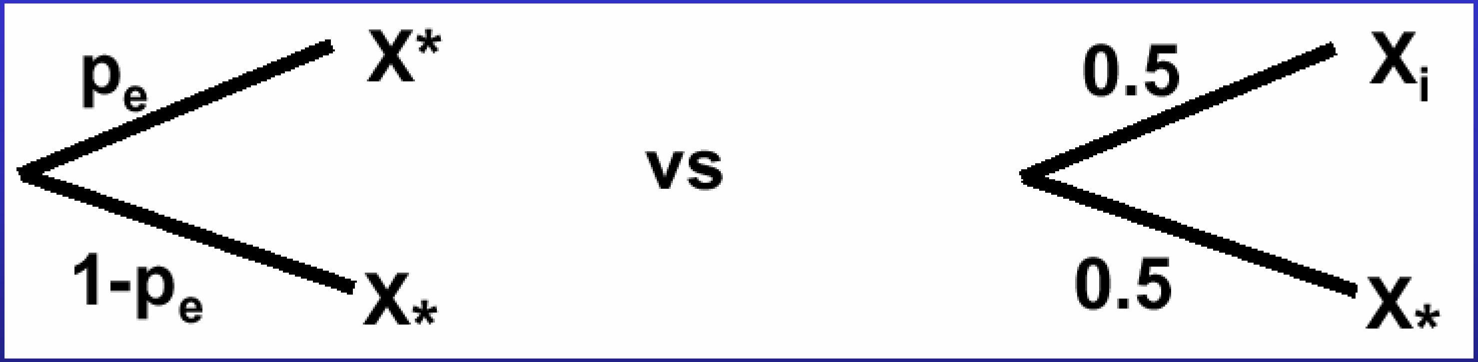
- The Design Vector is composed of fundamental, independent variables that define an architecture tradespace
  - Focuses on variables that have significant impact on attributes
  - Geometric growth of design space motivates a curtailed list of design variables

Obtaining User Preferences

1. Define attributes
2. Define applicable attribute ranges
3. Compose utility questionnaire (context)
4. Conduct utility interview with Customer/User
5. Find utility for each attribute U(X_i), and relative "weight" k_i

Interview Process

- New Method
- Avoid Certainty Equivalents to Avoid "Certainty Effect"
- Consider a "Lottery Equivalent"
  - Rather than Comparing a Lottery with a Certainty
  - Reference to a Lottery is Not a Certainty



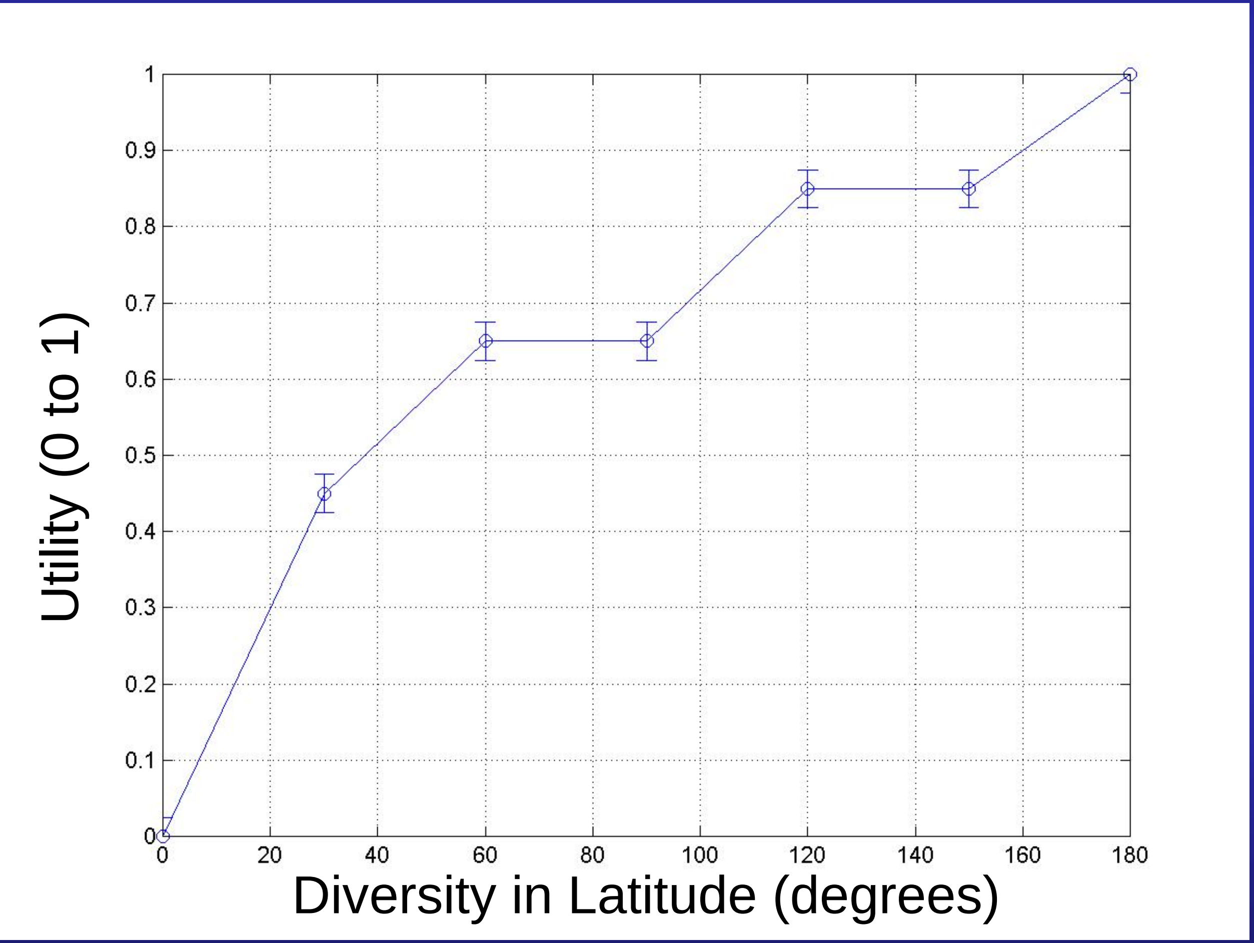
- Vary "p_e" until indifference between two lotteries. This is the Lottery Equivalence

Measuring Utility

- Psychometric considerations
  - Nature of interview
  - Context
  - Scale of response
  - Method obtained (bracketing)
  - Consistency and replicability (computer programs)
- Step-by-Step Procedure
  - Defining the Attribute X
  - Setting context
  - Assessment
  - Interpretation
  - Numerical approximation

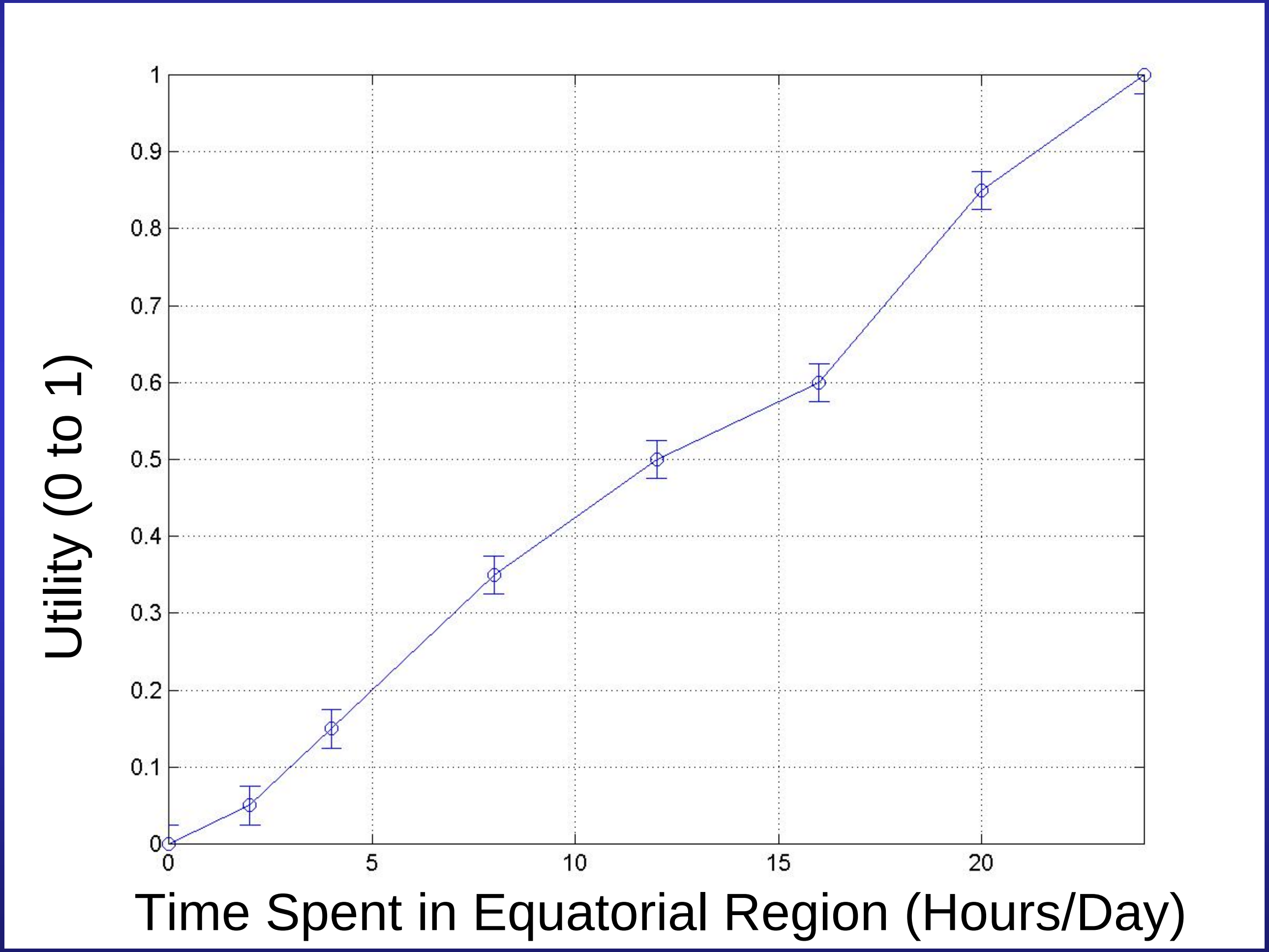
Diversity in Latitude Utility Curve

This attribute evaluates user preference for achieving a diversity in latitudes while under 1000 km, ranging from 0 to 180 degrees.



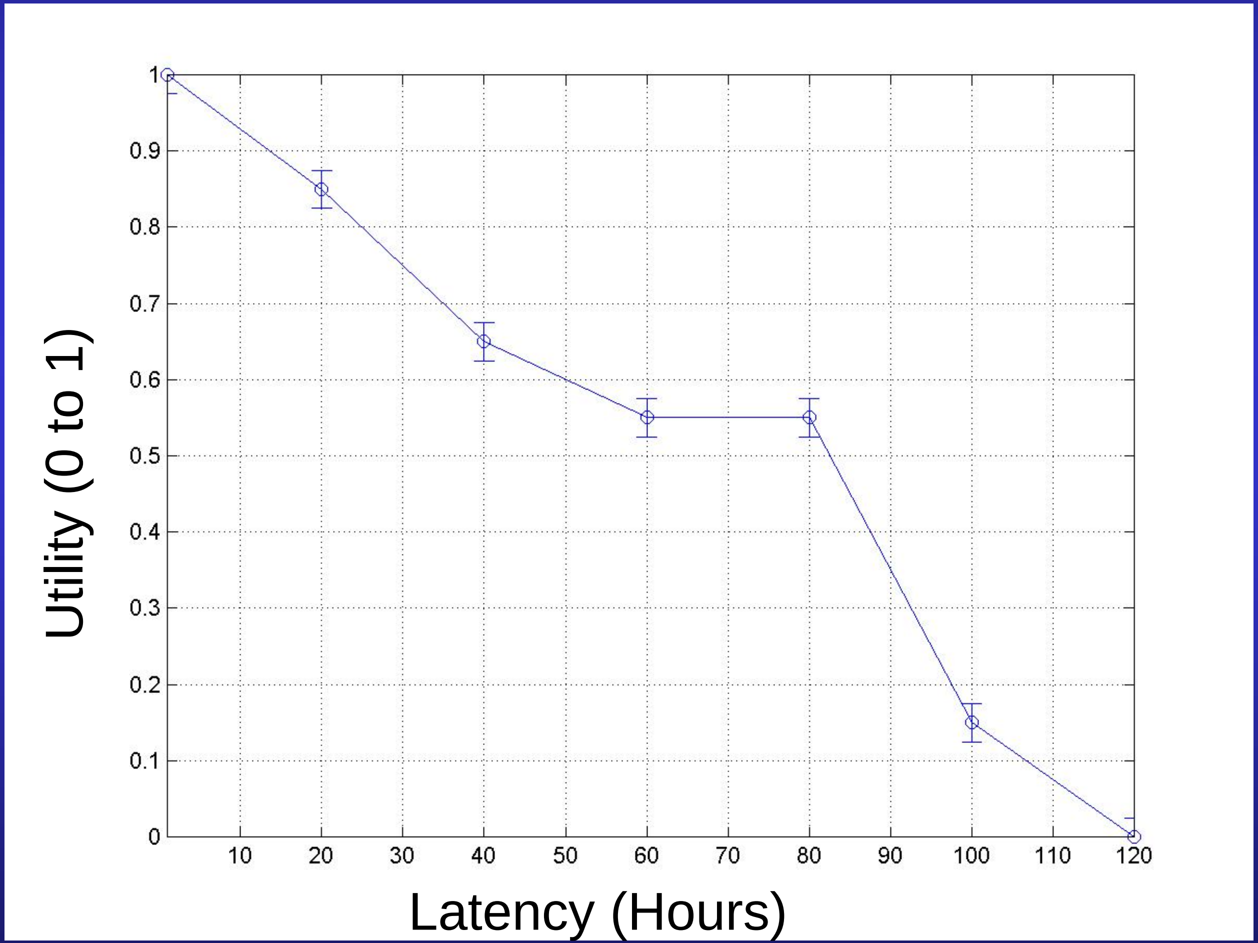
Time Spent in Equatorial Region Utility Curve

This attribute evaluates user preference for time spent in the equatorial region, defined as ± 20 degrees from the equator.



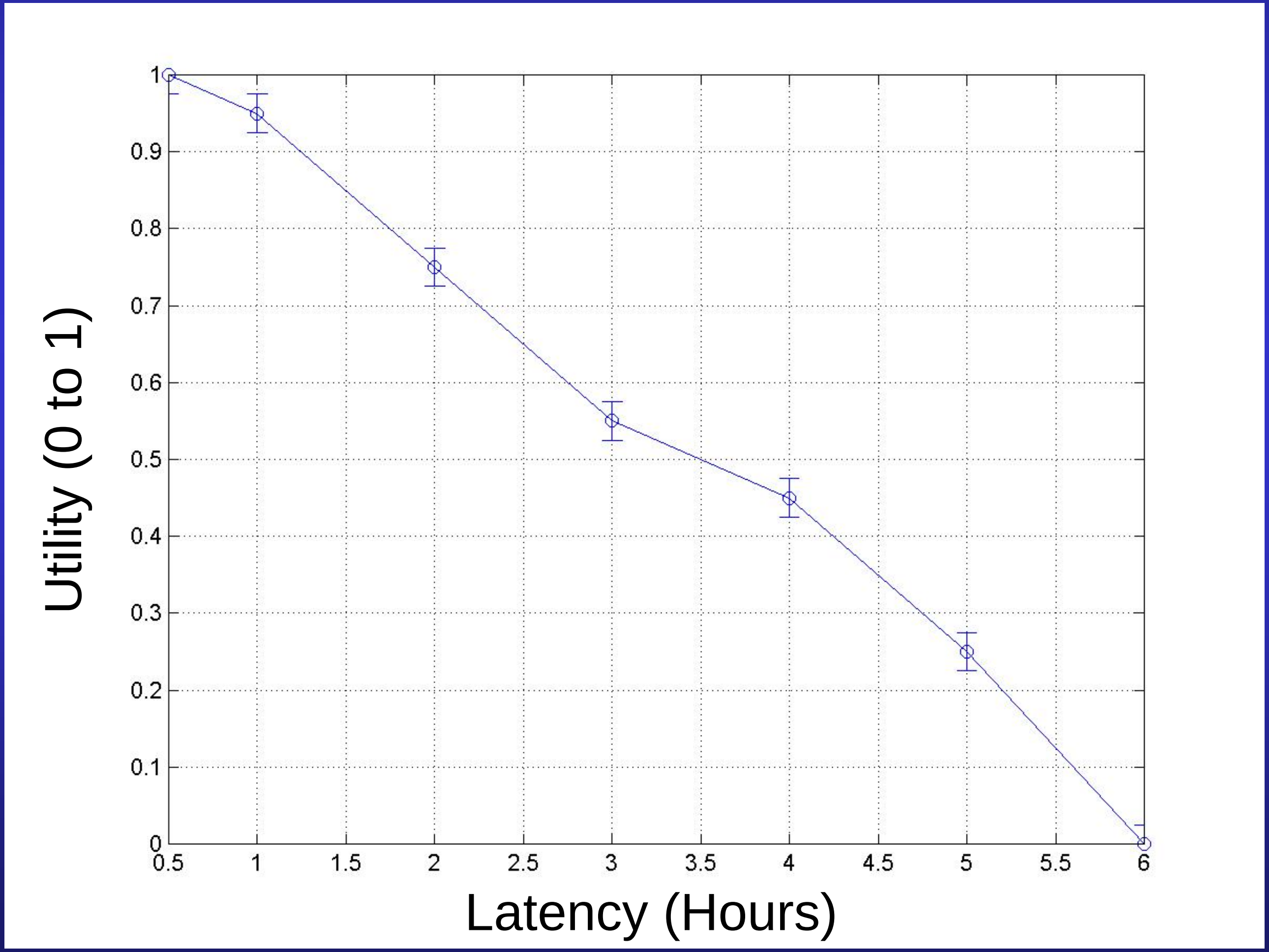
Latency Utility Curve (Science Mission)

This attribute evaluates user preference for s/c latency in terms of a science mission, where latency is defined as the time between satellite data dumps.



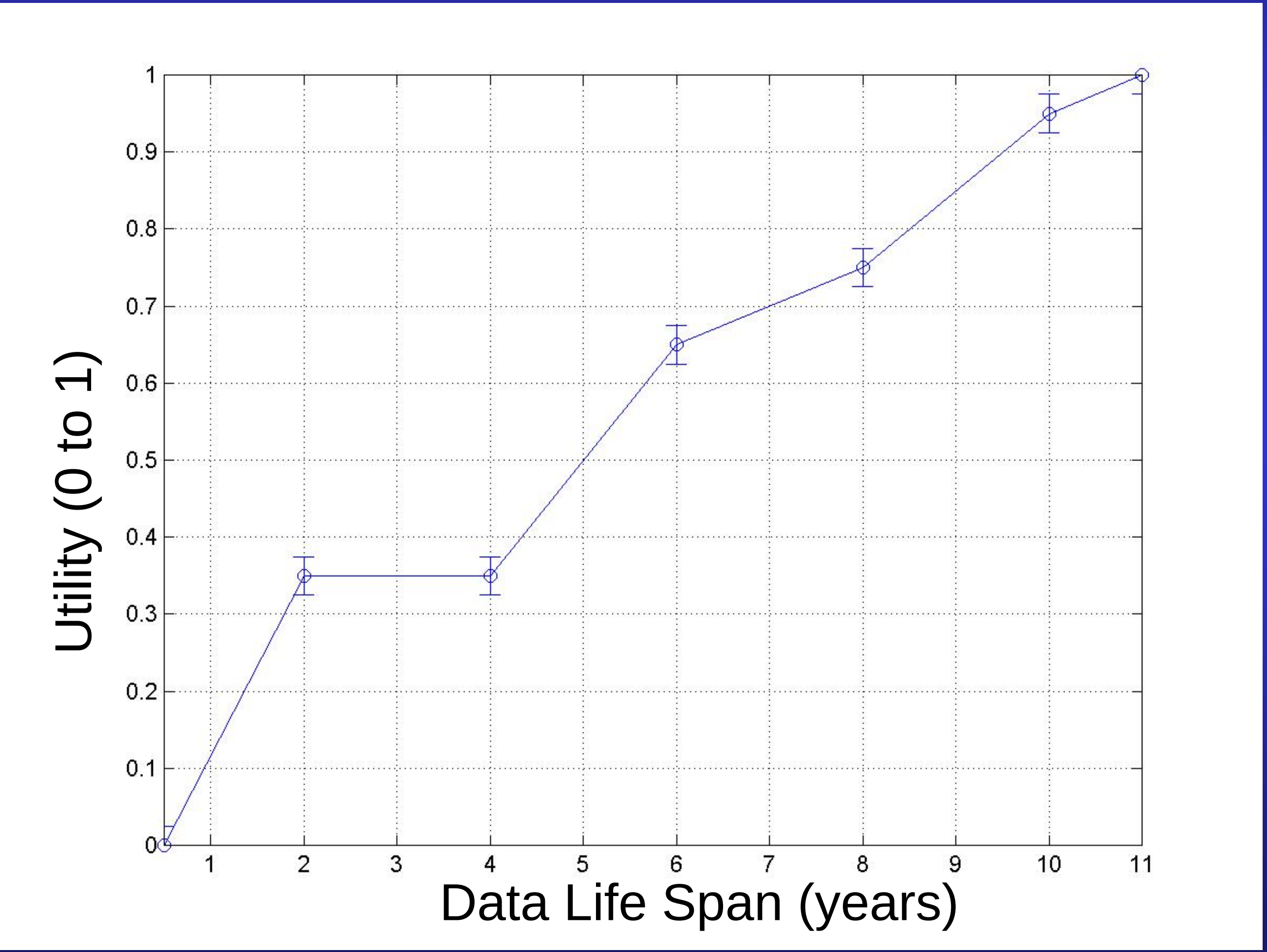
Latency Utility Curve (Tech Demo Mission)

This attribute evaluates user preference for s/c latency in terms of a tech demo mission, where latency is defined as the time between satellite data dumps.



Data Life Span Utility Curve

This attribute evaluates user preference for the life span of all the data entering the model, where the life span is the time between the first and last data sample



Quality Function Development

- Description:
  - A matrix to capture the influence a particular design variable has on the system attributes
- Expedites correlation of variables with attributes
- Enables ranking of design variables
- Enables reduction of design vector dimensionality

Quality Function Development (QFD)

		Range	0.5 - 11	150 - 1000	0 - 180	0 - 24	1 - 120		0 - 200 M$	
		Units	Years	Km	Degrees	Hours (per day)	Hours		USD (2002)	
		Attributes	**Data Life Span (Per Satellite)**	**Sample Altitude**	**Diversity of Latitudes contained in the Data Set**	**Time Spent in Equatorial Region**	**Latency**	**Total**	**Cost**	**TOTAL WITH COST**
			1	2	3	4	5		6	
Variables	**Units**	**Constraints**								
Perigee Altitude	m	150 < hp < 350	9	9	0	0	3	21	9	30
Apogee Altitude	m	150 < ha < 1500	9	9	0	6	3	27	9	36
Inclination	Degrees	0 < i < 90	0	0	9	9	3	21	6	27
delta-V	m/s	0 < mass < 500	9	0	0	0	0	9	9	27
Comm System Typ	-	AFSCN or TDRS	0	0	0	0	9	9	3	12
Propulsion Type	-	Chemical or Hall	6	0	0	0	0	6	6	12
Power System Typ	-	Solar or Fuel Ce	6	0	0	0	6	12	6	18
Mission Scenario	-	-	9	9	9	9	3	39	9	48

N-Squared Diagram

- Description:
  - A square matrix that captures the informational flow among system elements
- Assists the simulation interface management and integration

N-Squared Diagram

	Orbit	Spacecraft	Launch	Cost (TFU)	Mission Scenarios	Calculate Attributes	Cost (Lifecycle)	Utility	Outputs
Orbit									
Spacecraft	X								
Launch	X	X							
Cost (TFU)		X	X						
Mission Scenarios	X	X		X					
Calculate Attributes	X	X			X				
Cost (Lifecycle)		X		X	X				
Utility						X			
Outputs	X	X	X	X	X	X	X	X	

Information Flow

Satellite Enumerator

- Orbits – varies orbital parameters
- Spacecraft – varies physical satellite parameters
- Launch – specifies vehicle

Satellite Database

Mission Scenario Enumerator

- Applies expert rules
- Finds satellites which fit 4 mission scenarios according to expert rules

Satellite Database

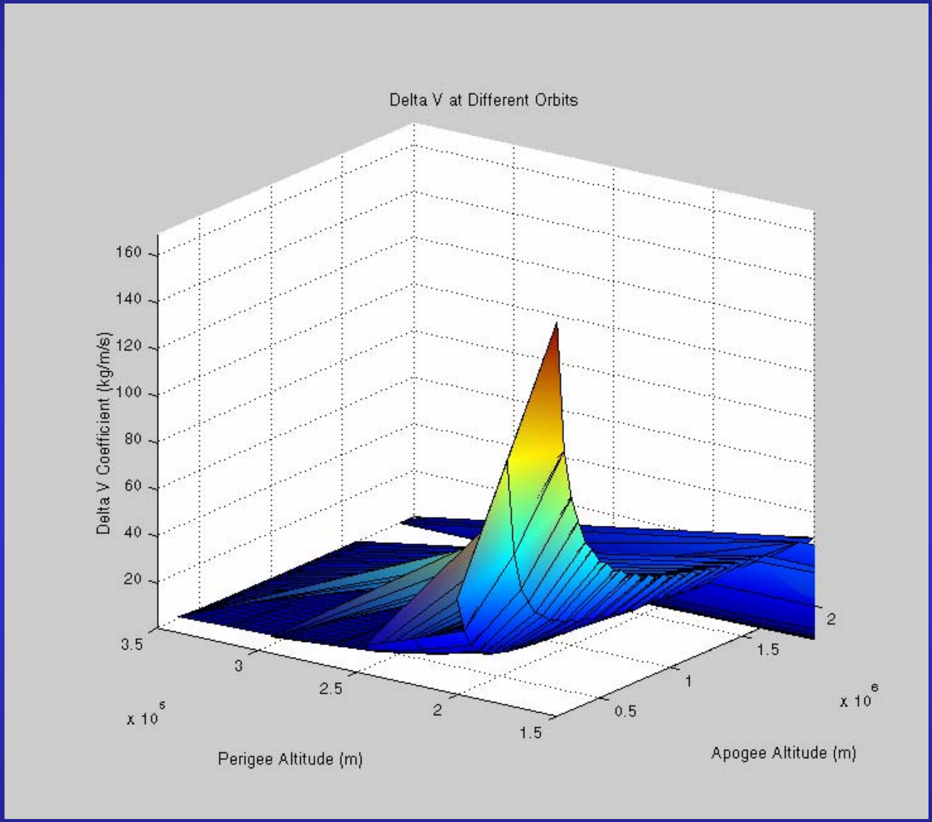
Enumerator Database

Simulator

- Takes mission scenarios (with chosen satellites)
- Calculates Attributes Cost and Utility

Orbits Database

- Plot shows an interesting region at low apogees and perigees
- Provides insights on how to better utilize database in the Mission Scenario module



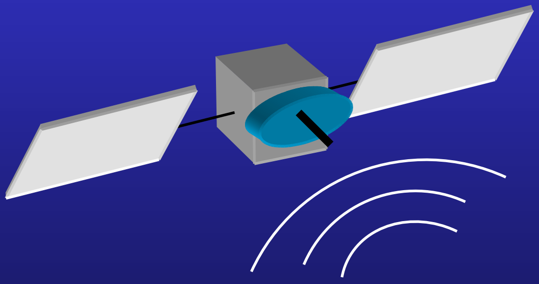
Spacecraft Module

Sub Modules

- Payload
  - -AFRL instruments
- Structures
- Thermal
- Power (SC or fuel cell)
- Propulsion (chemical or Hall)
- ADACS (0.1^0 pointing)
- Communication
  - -3 dB Link Margin

Outputs

- Total system mass
- Dimensions
- Volume
- Lines of code
- Data Latency
- Lifetime



Spacecraft Module

Payload

- All constant values as given in AFRL presentation. Based on using their instruments

Structures

- Assumes standard mass and power ratios for primary and secondary structures, cabling and mechanisms

Thermal

- Assumes standard mass and power ratios for thermal subsystem

Power

- Total power needed is calculated by summing power requirements of all other systems.
- Two options : Fuel Cells or Solar Arrays

Propulsion

- This module only sizes the propulsion hardware
- Two options: Chemical (I_{sp} 350) or Hall (I_{sp} 1500)

Spacecraft Module

- The Spacecraft Module runs all the sub-modules and uses their output to compile mass, fuel, volume, dimension and lifetime estimates for the spacecraft as well as software and TFU costs.
  - Note: The power estimate was already calculated in the power module.
- The module outputs three lifetime estimates: 1) assuming fuel only used for station keeping, 2) assuming station keeping and de-orbit and 3) assuming orbital insertion (from a circular perigee orbit), de-orbit and station keeping

Spacecraft Module

Mass:

- Dry mass
- Propulsion mass
- Mass breakdown (individual subsystem masses)
- Total system mass

- Volume
  - Cylinder diameter
  - Cylinder side
  - Total Volume

Spacecraft Module

Spacecraft Module

- The spacecraft module estimates total amount of software needed, amount of storage space needed onboard, processing hardware needed and
- The module outputs a data latency value which is the longest length of time possible between receiving data.
- TFU cost is estimated using SMAD model

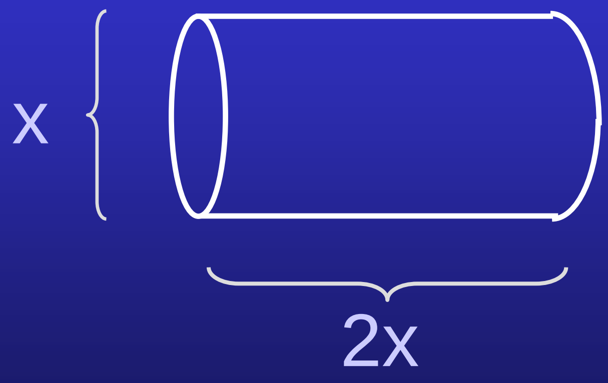
Orbits & Spacecraft

Orbits

- Varying: apogee, perigee, inclination
- Outputs include:
  - Orbital period
  - Minimum and maximum latitude encountered
  - Dynamic pressure coefficient
  - Vector of altitudes with respect to time

Spacecraft

- The spacecraft will be delivered to it's final orbit by the launch vehicle
- Spacecraft is a 1:2 cylinder (Drag calculations & S/C dimensions)
- Coefficient of Drag=1.7



Cost Module

Description

- Includes spacecraft, operations, launch, and program level costs
- Uses CERs for spacecraft/program level
- Uses NASA's Operations Cost Model
- Incorporates 95% learning curve
- Discounts costs at a 1.9% rate

Key Assumptions

- Assumes small satellites (20-400 kg)
- Costs in FY2000, inflated to FY2002
- Assumes payment for S/C is made on year of launch (for discount)
- Annual operations cost is yearly constant for one S/C, another constant for 2 parallel S/C (before discounting)

Scenarios

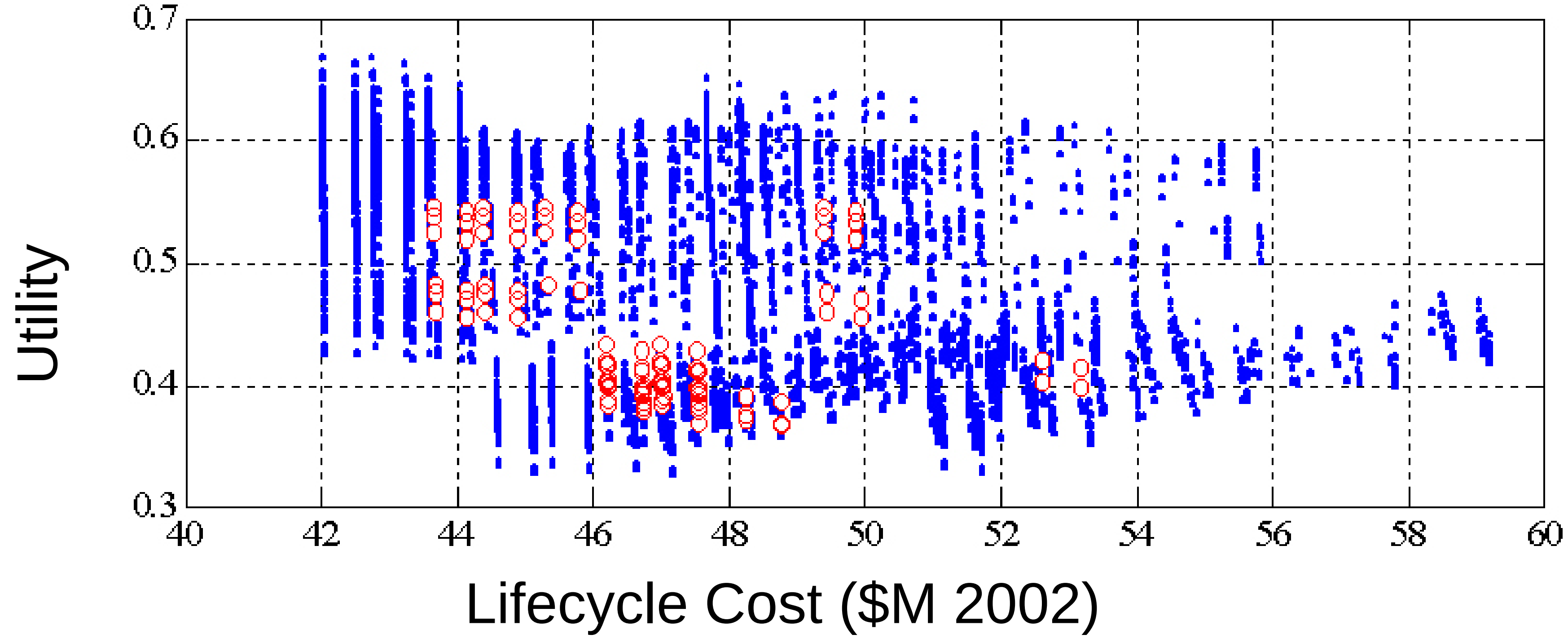
Sample Altitude:

- Hypothesize a new ground station
- Ground station will significantly increase data life span as compared to current systems
- Uncertain long-term funding
  - You have a 45% chance of getting 11 years (best) and
  - 55% chance of getting .5 years (worst)

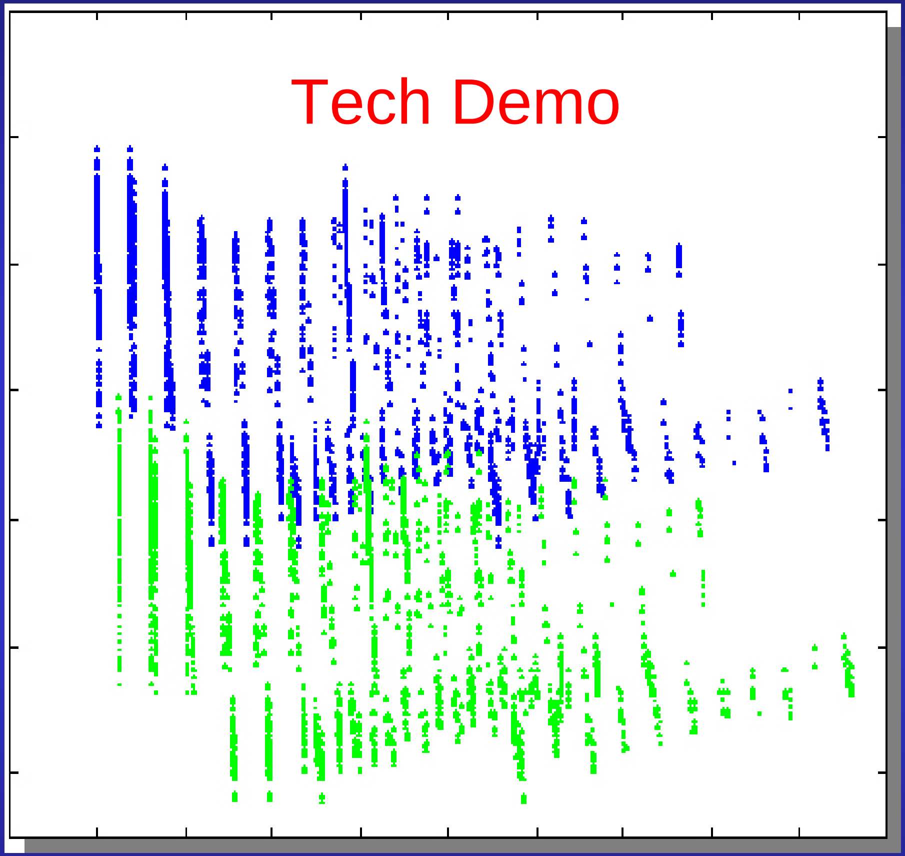
    OR

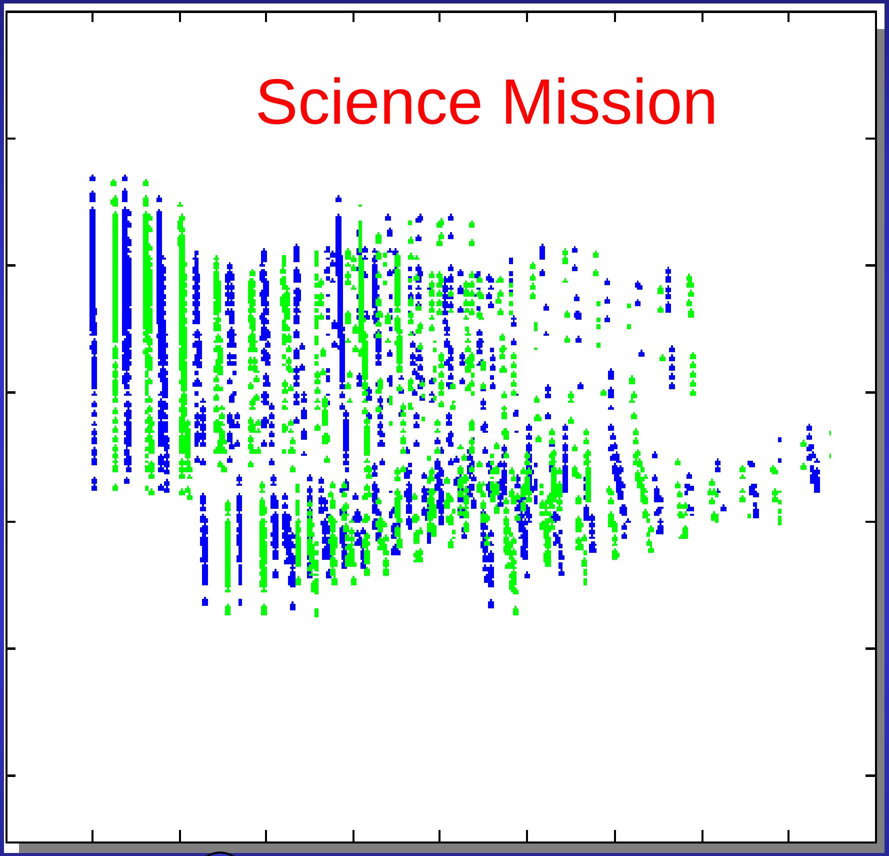
  - 50% chance of getting 2 years (best) and
  - 50% chance of getting 0.5 years (worst)

Possible Results for STEP 1 mission



Tech Demo vs. Science Mission

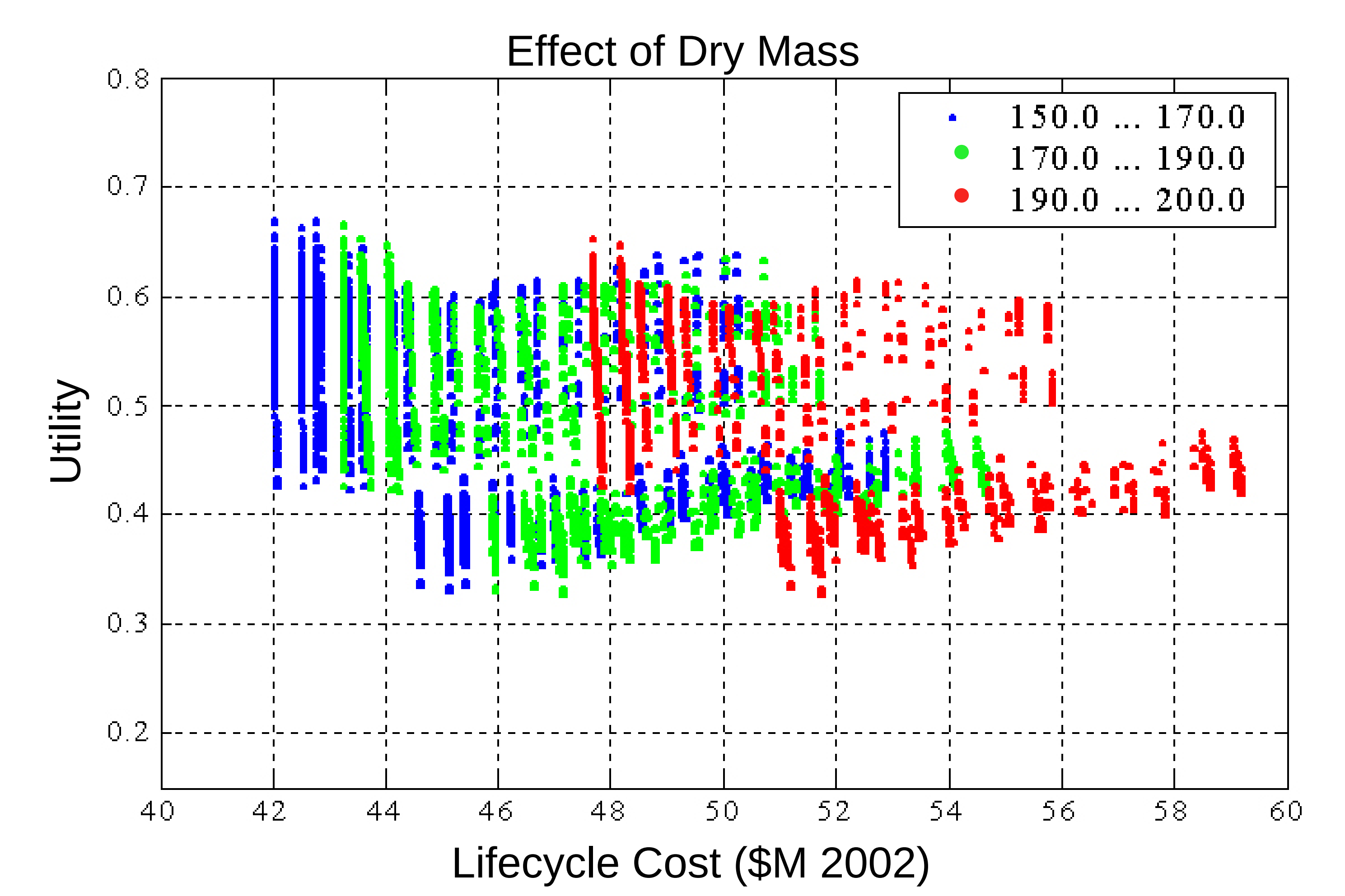




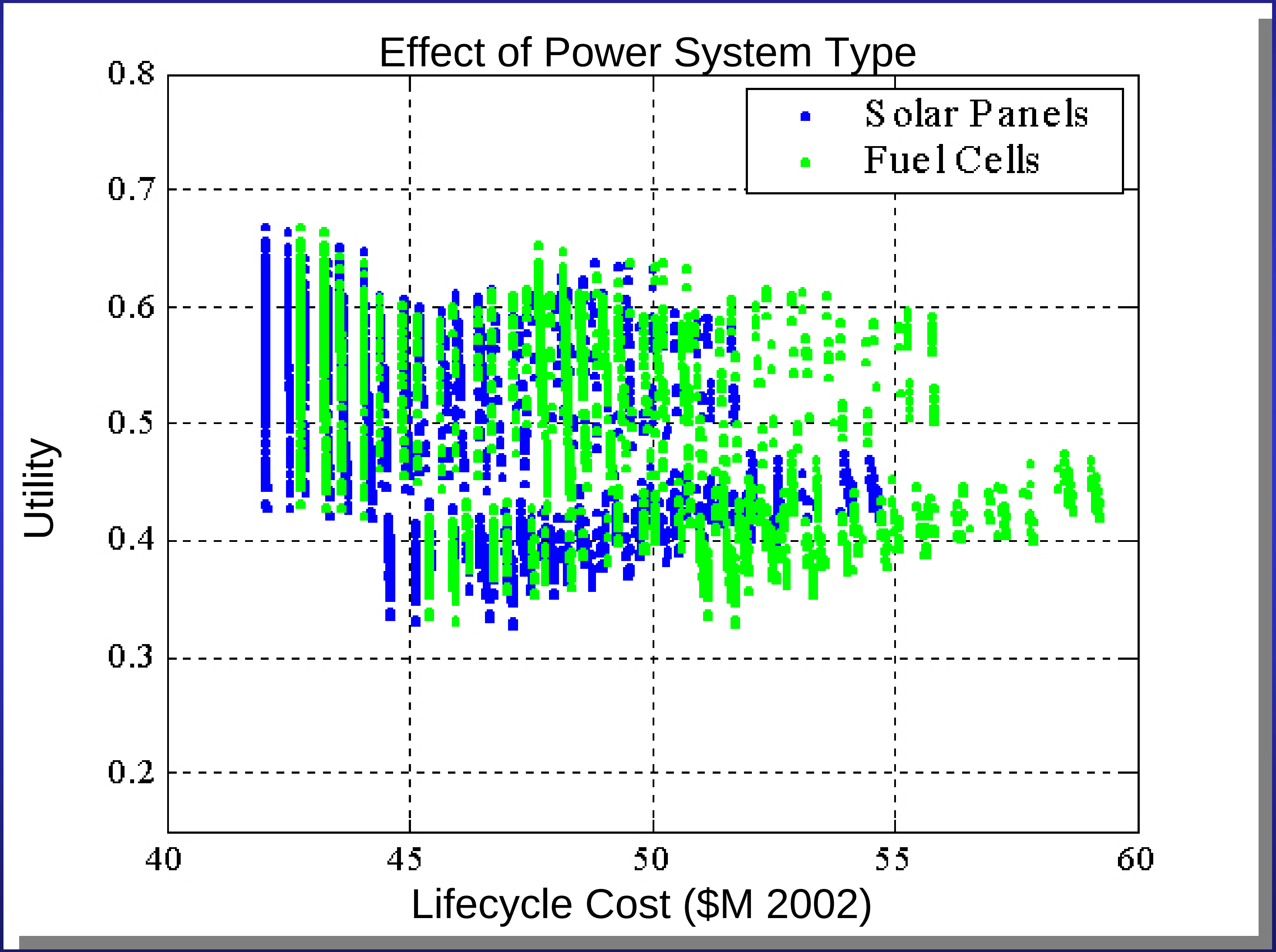
Low Gain Omni-directional Antenna

High Gain Actuated Antenna

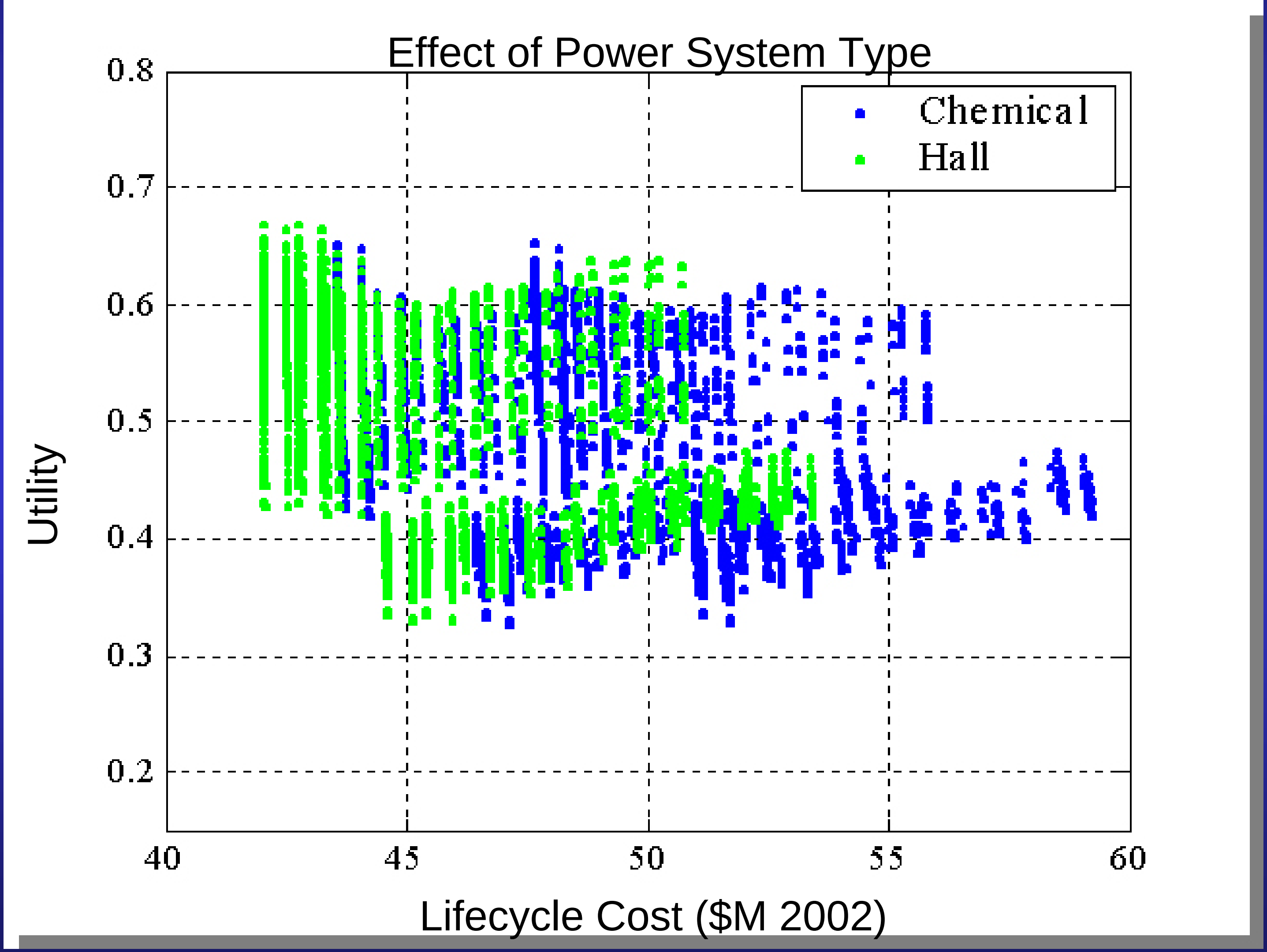
Cost Drivers: Dry mass



Cost Drivers: Power Source



Cost Drivers: Thruster Type



Power and Pyrotechnic

- Calculates average and peak power requirements for all modes
- Selects and sizes solar arrays
  - Based on EOL average load and battery charging
  - Type of solar cell (database)
  - Solar array configuration
  - Mass, area, and dimensions of arrays
- Selects and sizes secondary/primary batteries
  - Secondary based on eclipse average load
  - Primary based on launch / insertion requirements
  - Battery couple type
  - DOD %, cycle life, etc…
  - Mass, volume, and dimensions of batteries
  - Optional redundancy
- Estimates mass of power regulation and control based on power output.

Launch Module

Description

- Selects a Launch Vehicle based on the following
  - Minimum Cost
  - Spacecraft Total Mass
  - Spacecraft Dimensions
  - Perigee Altitude
  - Orbital Inclination

Key Assumptions

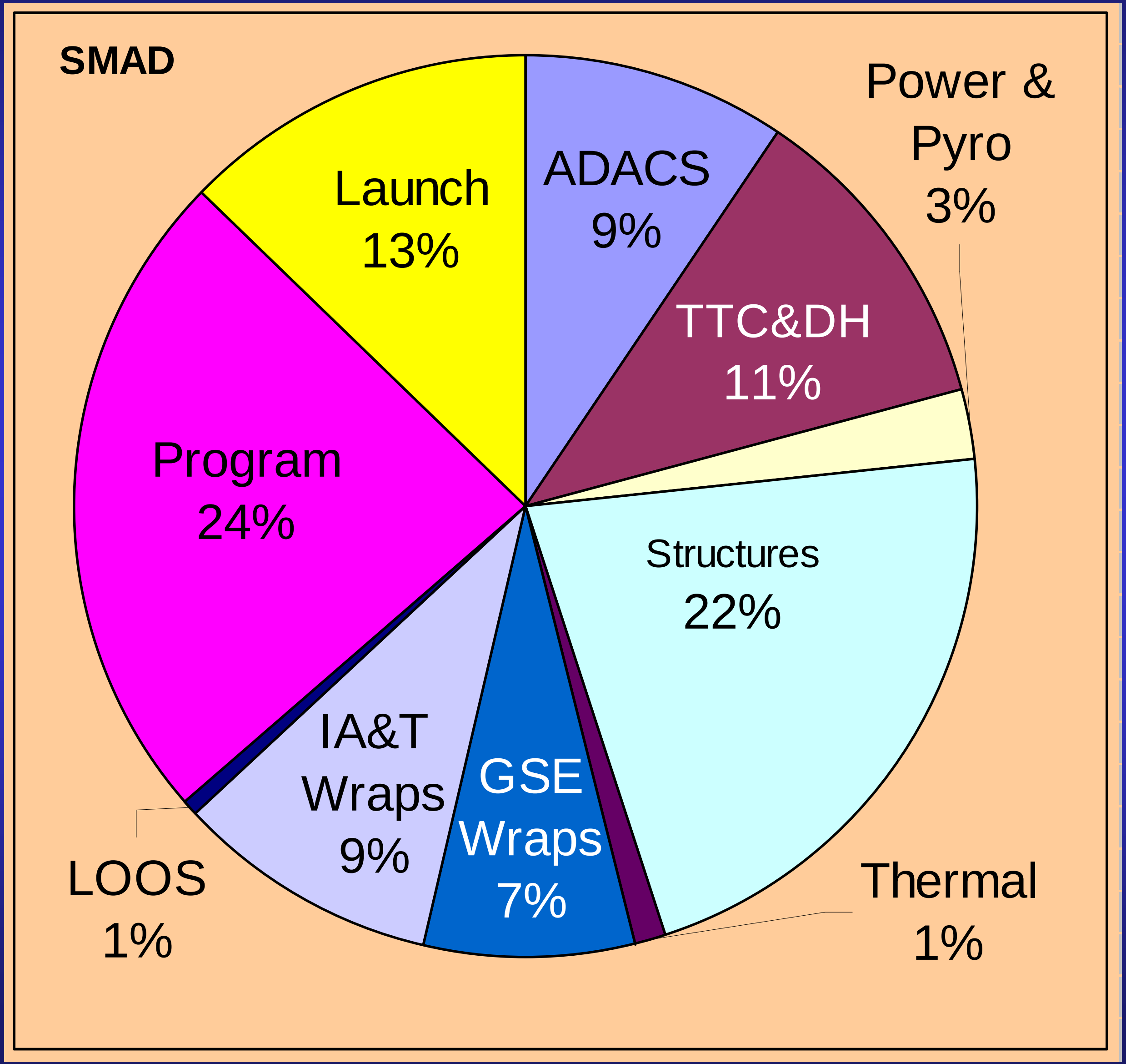
- Must be launched on a US vehicle
- Scalable spacecraft
  - Dimensions extracted from assumed densities
- One spacecraft per launch vehicle

Database:Sample SATDB Entry

data_error_flag	0		**payload_mass**	20.5
bad_launch_flag	0		**dry_mass**	196.0718
id	1000		**prop_mass**	8.9422
inclination	1.5708		**total_mass**	205.014
alt_perigee	200000		**latency**	2.12E+04
alt_apogee	200000		**lifetime**	0.2726
comm_arch	0		**lifetime_raw**	0.2726
total_delta_v	700		**volume**	2.5226
prop_type	0		**diameter**	1.171
power_type	1		**length**	2.3421
ant_gain	1		**max_avg_power**	486.7966
period	5.31E+03		**max_peak_power**	486.7966
time_eq	19020		**tfu_cost**	2.14E+07
min_lat	-1.545		**lv_name**	'Minotaur'
max_lat	1.562		**lv_cost**	12500000
delta_v	48.4051		**lv_site**	Vandenberg or Kodiak'
alt_vector	[89x1 double]		**arch_id**	28
bus_mass	175.5718			

- Some values are directly from the design vector
- Other values are derived from the design vector using the orbits, spacecraft, and launch modules

SMAD Cost Breakdown Chart



Credits

- Presentation Document
  - Bobak Ferdowsi
- Presenters
  - Mirna Daouk
  - Geoff Huntington
  - George Leussis
  - Kevin Duda
  - Nirav Shah