SEAri Working Paper Series

Title: Example MATE Projects

Author: Various

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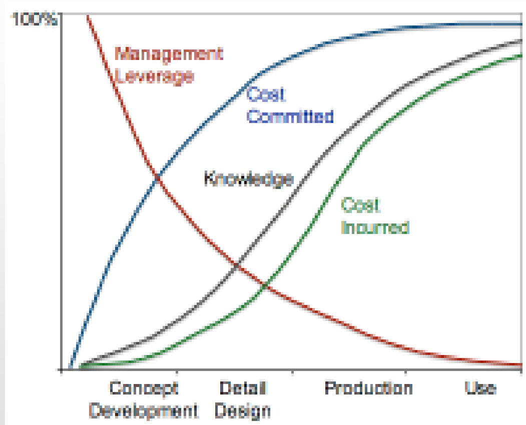
Systems Engineering Advancement Research Initiative

Multi-Attribute Tradespace Exploration (MATE)

Example Projects
as of September 2008

Value is primarily determined at the beginning of a program



After Fabrycky and Blanchard 1991

How can we make good decisions?

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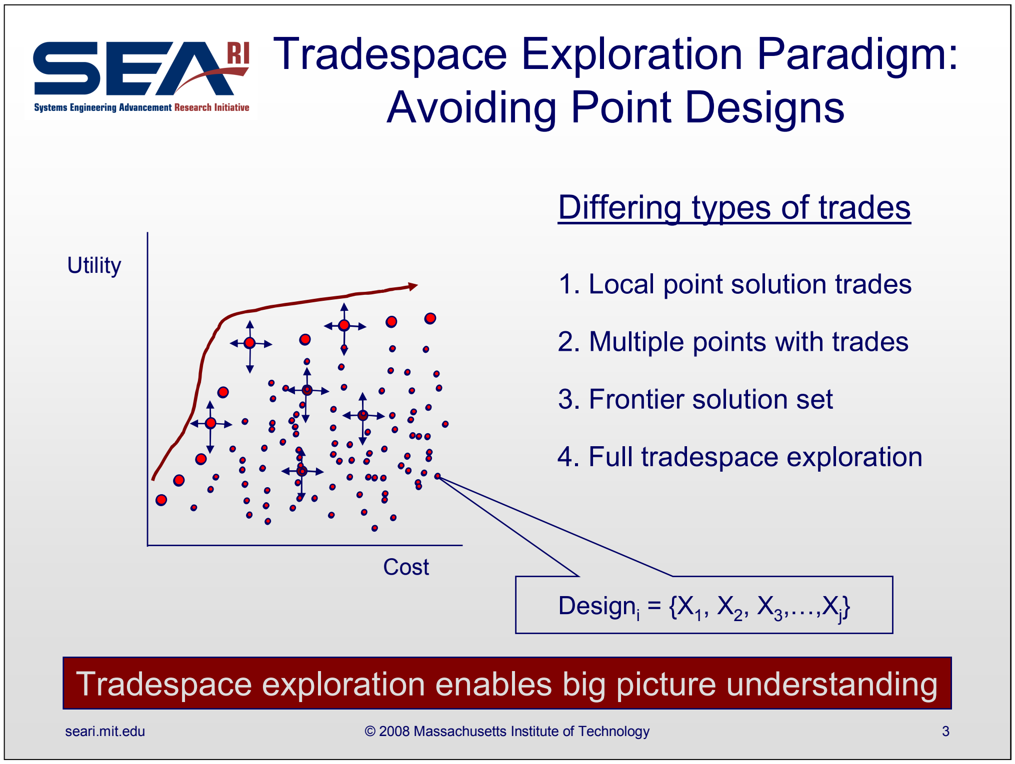
2

This is a chart students may have seen before. The point is, upfront activity CONSUMES very little money, but COMMITS a great deal, and changes from these early decisions gets harder and hard to do (and more and more expensive!). So we want to do up-front work, and make upfront decisions, right.

But (not on chart) UNCERTAINTY Is very high early in the program, so how can good decisions be made?



When contemplating the infinite variety of solutions to a design problem, we can

-1) Guess the right solution (better guess right…)

0) Analytically verify one solution (if wrong, start over)

1) Explore the neighborhood of our solution to see if there might be better solutions available. This is the first alternative presented on the chart. The graphic shows a "tradespace" plotting the utility (ability to satisfy user needs) against the cost of a wide variety of designs. Each design is represented by a dot on the tradespace. The utility and cost are determined by a wide variety of design features (X1, X2,…etc). Note for now we will not consider HOW these utilities and costs are determined; this is a notional discussion. Note that our selected solution is only OK, there are better and cheaper solutions out there.

2) We could explore several more solutions, and even parametrically examine their neighbors. This is current good (if not best) practice.

3) If we explore enough solution we may get a feal for where the "Pareto frontier" is - the set of possible solutions which cannot be made cheaper without a sacrifice in utility, or conversely cannot be made better without an increase in cost. Intuitively, these are the preferred solutions to pick from

4) Finally, with even rough models (and a lot of computer power - but that is easy these days!) we can explore MANY solutions and come to a full understanding of the nature of the trade space. This means not just finding the best solution for the single case plotted here, (which assumes some current user set and conditions), but which solutions might be more resistant to future changes, useful for other users or purposes, expandable or adaptable, etc.

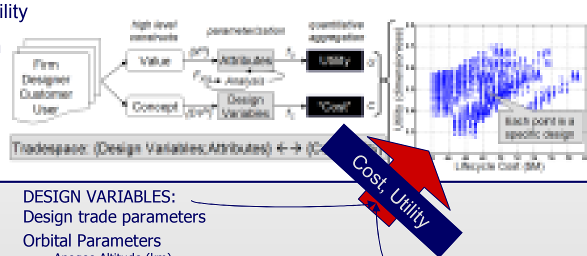
Note this "tradespace" understanding may be analytical; it may also be tacit knowledge in the head of experienced personnel. The Toyota "Chief Engineer"

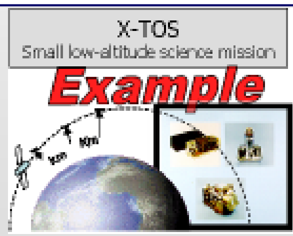
Tradespace Exploration Coupled with Value-driven Design

Many system designs can be compared through ***tradespace exploration***:

1. Elicit "Value" with attributes and utility
2. Generate "Concepts" using design variables and cost model insights
3. Develop models/sims to assess designs in terms of cost and utility

Models and simulations determine attribute "performance" of many designs (1000s to 10000s or more)





DESIGN VARIABLES:
Design trade parameters

Orbital Parameters
- Apogee Altitude (km)
- Perigee Altitude (km)
- Orbit Inclination (deg)

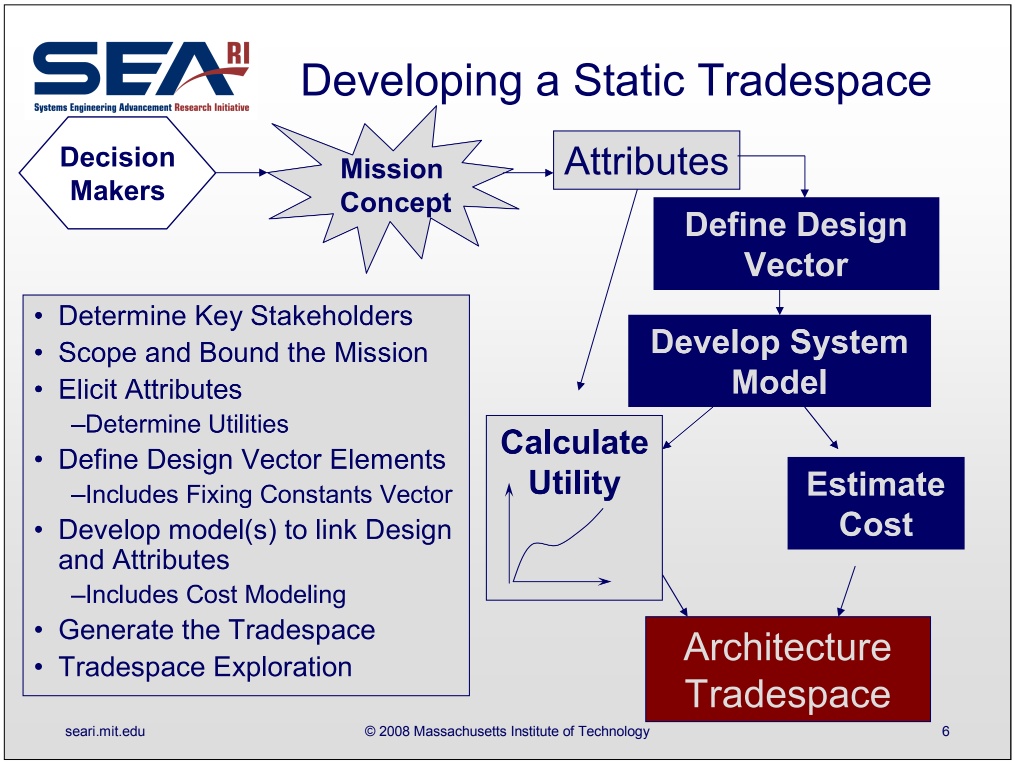
Spacecraft Parameters
- Antenna Gain
- Communication Architecture
- Propulsion Type
- Power Type
- Total Delta V

ATTRIBUTES:
Design decision metrics
- Data Lifespan (yrs)
- Equatorial Time (hrs/day)
- Latency (hrs)
- Latitude Diversity (deg)
- Sample Altitude (km)

Assessment of cost and utility of large space of possible system designs

What's in a Name?

- Multi-Attribute
  - "Multi": reflects the multi-criteria nature of the design-value problem space
  - "Attribute": reflects the focus on decision maker-defined metrics for success, i.e., value-focused
- Tradespace Exploration
  - "Tradespace": reflects the broad consideration of design alternatives and the structured tensions underlying differences between and among options
  - "Exploration": reflects discovery and communication of patterns in the design space, with no "best" destination, as opposed to optimization



One can analytically create tradespace understanding in any system that can be decomposed into a finite set of Attributes - a set of things that can be quantified and which the user values.

A set of designs can then be assessed by quantifying them in a “design vector”, usually a very large set of designs generated by parametrically varying a moderate number of physical attributes.

A system model (often a very coarse one will do) is then used to calculate the attributes (and hence user utility) for each of the possible designs, and cost model (usually only a very coarse one is available!) is used to estimate the cost. These two values determine the position of the design on a trade-space of the type shown in the last slide.

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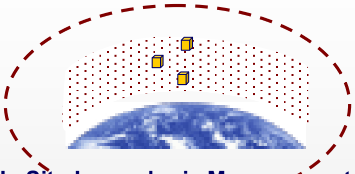
MATE Project Examples

13 Case Studies

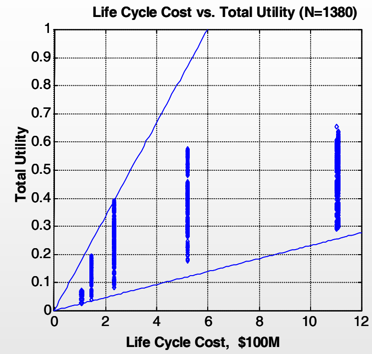
September 2008

Project 1: A-TOS

Swarm making in-situ ionosphere measurements



In Situ Ionospheric Measurements



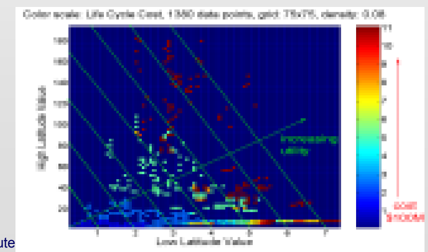
DESIGN VARIABLES (7)

- Bulk Orbit Variables
  - Swarm inclination (deg) — 63.4
  - Swarm perigee altitude (km) — 200 – 800
  - Swarm apogee altitude (km) — 200 – 800
  - Swarm argument of perigee (deg) — 0
  - Number of orbit planes — 1
  - Swarms per plane — 1
- Swarm Orbit Variables
  - Subsats per swarm — 1 – 26
  - Number of subplanes in each swarm — 1 – 2
  - Number of suborbits in each subplane — 1 – 4
  - Yaw angle of subplanes (deg: vector) — ±60
  - Maximum satellite separation (km) — 0.001 – 200
- Non-orbit Variables
  - Mothership — (yes/no)

ATTRIBUTES (2)

- "Value" in Low latitude mission, "Value" in High latitude mission

Number of Designs Explored: 1380



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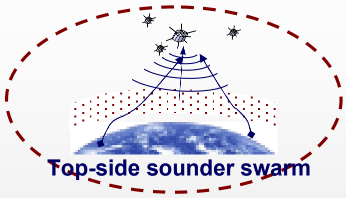
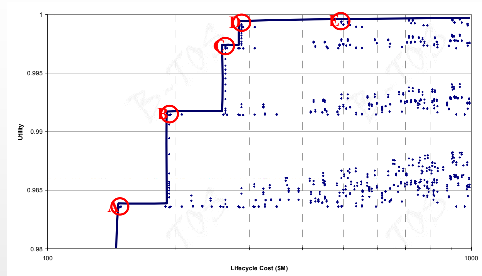
Project 2: B-TOS

Hills swarm making ionosphere soundings



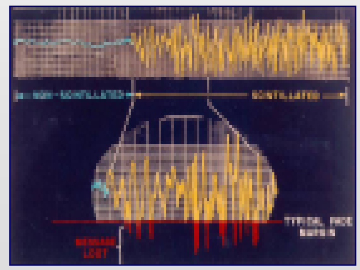


DESIGN VARIABLES (6)

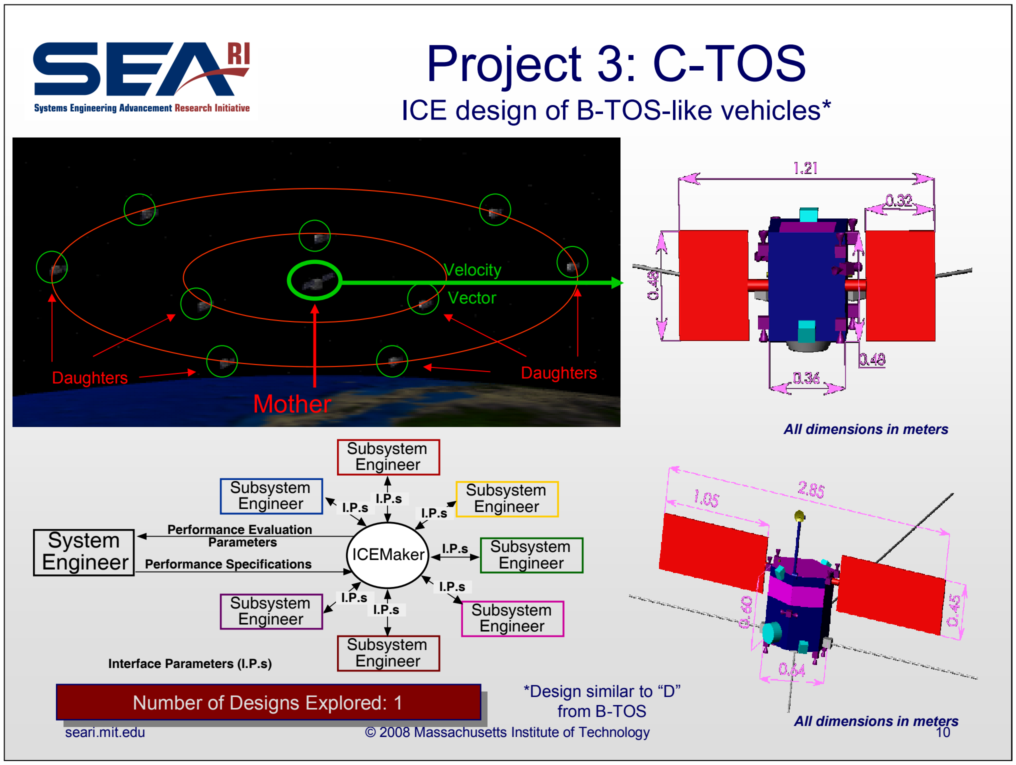
- Large Scale Arch
  - Circular orbit altitude (km) — 1100, 1300
  - Number of Planes — 1, 2, 3, 4, 5
- Swarm Arch
  - Number of Swarms/Plane — 1, 2, 3, 4, 5
  - Number of Satellites/Swarm — 4, 7, 10, 13
  - Radius of Swarm (km) — 0.18, 1.5, 8.75, 50
- Vehicle Arch
  - 5 Configuration Studies — Trades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

ATTRIBUTES (5)

- Spatial Resolution (deg^2), Revisit Time (min), Latency (min), Accuracy (deg), Inst. Global Coverage (%),



Number of Designs Explored: 4033


SEA RI
Systems Engineering Advancement Research Initiative
Project 3: C-TOS
ICE design of B-TOS-like vehicles*
Velocity
Vector
Daughters
Daughters
Mother
1.21
0.32
0.48
0.48
0.34
All dimensions in meters
Subsystem Engineer
Subsystem Engineer
Subsystem Engineer
Subsystem Engineer
Subsystem Engineer
Subsystem Engineer
Subsystem Engineer
System Engineer
Performance Evaluation Parameters
Performance Specifications
ICEMaker
I.P.s
Interface Parameters (I.P.s)
2.85
1.05
0.60
0.45
0.64
All dimensions in meters
Number of Designs Explored: 1
*Design similar to "D" from B-TOS
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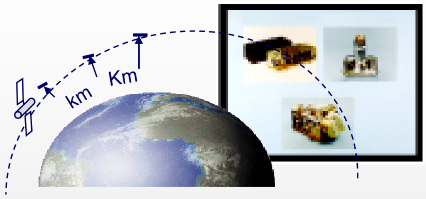
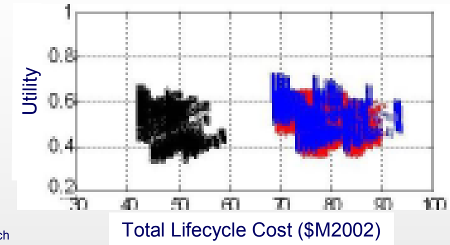
Project 4: X-TOS

Single-Vehicle in-situ density measurements





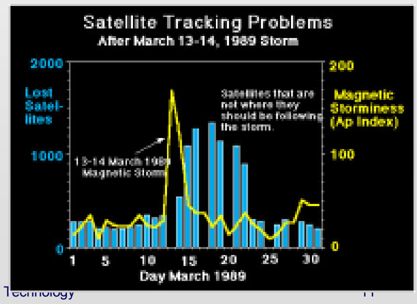
DESIGN VARIABLES (9)

- Mission Design
  - Scenario — 1 sat, single launch; 2 sats, sequential launch; 2 sats, parallel launch
- Orbital Parameters
  - Apogee altitude (km) — 200-2000
  - Perigee altitude (km) — 150-350
  - Orbit inclination (deg) — 0, 30, 60, 90
- Physical Spacecraft Parameters
  - Antenna gain — low, high
  - Communication architecture — TDRSS, AFSCN
  - Propulsion type — electric, chemical
  - Power type — solar, fuel cell
  - Delta_v (m/s) — 200-1000

ATTRIBUTES (5)

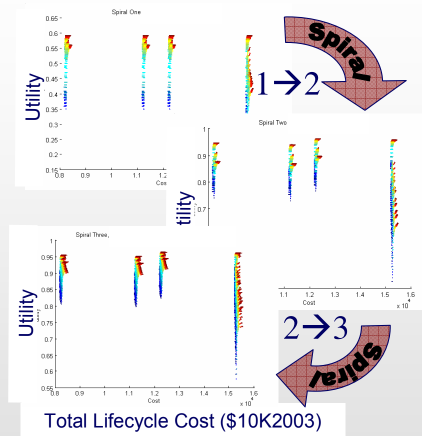
- Data lifespan (mos), Sample altitude (km), Latitude diversity (deg), Equatorial time (hr/day), Latency (hrs)

Number of Designs Explored: 50488



Project 5: Small Dia. Bomb

Small kinetic munitions

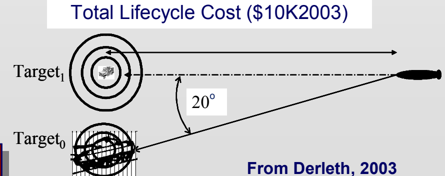


DESIGN VARIABLES (5)

- Bomb Parameters
  - Wing aspect ratio — 0.1-2 (Δ= 0.05)
  - Guidance Type — Inertial or GPS
  - Explosive weight (lbs) — 150-220 (Δ=10)
  - Diameter (in) — 3-9 (Δ=1)
  - Fuel Weight (lbs) — 10-25 (Δ=5)

ATTRIBUTES (2-4)

- Spiral One
  - Standoff Distance (mi), Sorties (flights/target)
- Spiral Two
  - Standoff Distance (mi), Sorties (flights/target)
- Spiral Three
  - Standoff Distance (mi), Sorties (flights/target), Retarget Time (secs), Loiter Time (hrs)



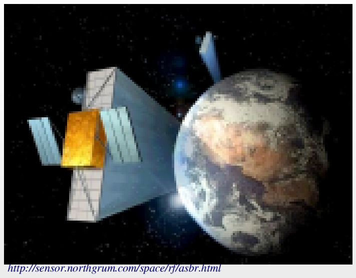
Number of Designs Explored: 8700+8700+35000

From Derleth, 2003

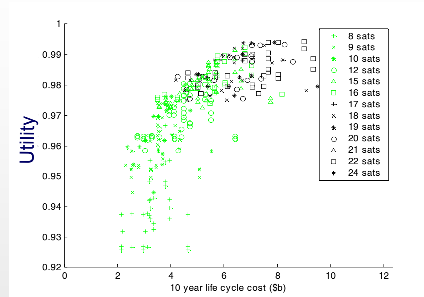
SEA RI
Systems Engineering Advancement Research Initiative

Project 6: Space-Based Radar

Satellite radar constellation for radar missions



http://sensor.northgrum.com/space/rf/asbr.html

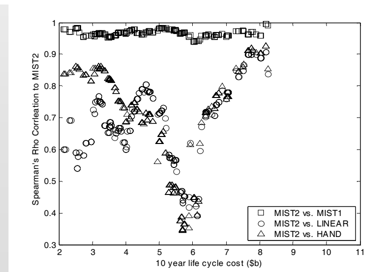


<u>DESIGN VARIABLES (5)</u>

- Orbital Parameters
  - Orbit Altitude (km) — 800,1000,1200,1400
  - Walker Constellation Type (sats) — 8-24 (not 11,14,23)
- Physical Spacecraft Parameters
  - Scan Angle (deg) — 5x5,20x5,30x15,45x15
  - Aperture Area (m^2) — 40,70,100
  - Technology Level (yr) — 2002,2005,2010

<u>ATTRIBUTES (7)</u>

- Tracking Area (num 10 mi^2 boxes), Min Detect Speed (mph), SAR Resolution (m), SAR Area (mi^2), Geo Accuracy (m), Gap Time (min), Center of Gravity Area (num 100 mi^2 boxes)



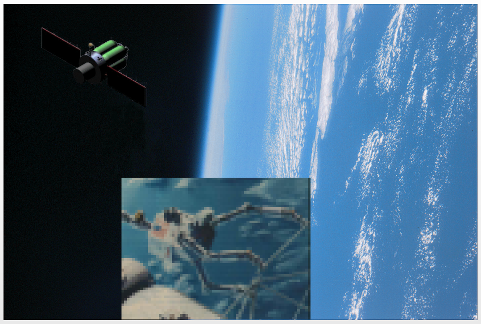
Number of Designs Explored: 1872

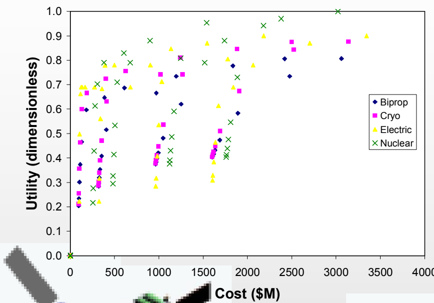
From Spaulding, 2003

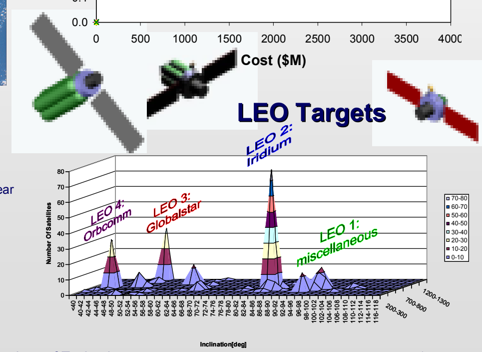
![SEAri logo] Systems Engineering Advancement Research Initiative

Project 7: Space Tug

General purpose orbital service vehicle







DESIGN VARIABLES (3)

- Physical Spacecraft Parameters
  - Tugging Capability — low, med, high, extreme
  - Propulsion Type — storable-bi, cryogenic, electric, nuclear
  - Propellant Mass (kg) — 0-50000

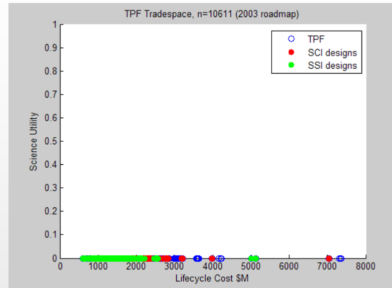
ATTRIBUTES (3)

- Capability (kg), DeltaV (m/s), Fast (y/n)

Number of Designs Explored: 137

Project 8: Terrestrial Planet Finder

A “Big Science” project

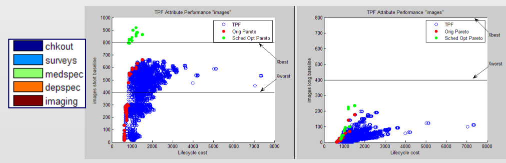


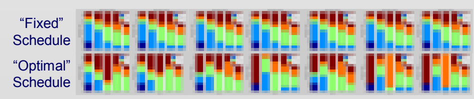
DESIGN VARIABLES (8+2)

• Orbit Type	{L2, LO, DA}
• Num Apertures	4,6,8,10
• Wavelength	7,10,20 microns
• Interferometer Type	{sci, ssi, tsi}
• Aperture type	{circular optics, strip optics}
• Aspect Ratio	{multi, const}
• Aperture Size	Variable
• Interferometer Baseline	Variable
• [Schedule]	[0-1 for each obs type]
• [Design Lifetime]	5 or 10

ATTRIBUTES (4+2, 2+1)

- Science
  - Num of Surveys (num), Num Medium Spectroscopies (num), Num Deep Spectroscopies (num), Number of Images (um) [Num Long Baseline Images (num), Num Short Baseline Images (num),
- Agency
  - Lifecycle Cost ($M), Operational Lifetime (years), [Annual Ops Cost $M)]



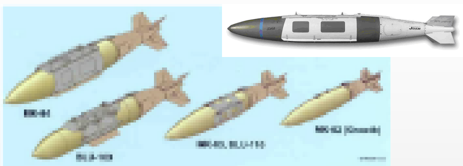


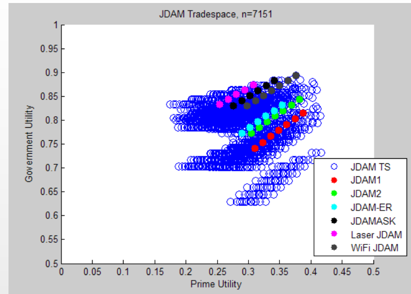
Number of Designs Explored: 10611

From Ross, 2006

Project 9: JDAM

Bomb kit for precision guidance





DESIGN VARIABLES (8+3)

- Planform — 1-3, {none, strakes/tail fins, canard/wing}
- Navigation System — 1-5, include various INS/GPS/AC update
- Targeting System — {none, fixed data, remote comm.}
- Goal Aircraft Compatibility — num
- Software — {simple, med, complex}
- Aircraft Carrier Compatibility — yes/no
- Unit Price Charged — 0-40000
- In-flight Communication — yes/no
- [Laser Sensor, Wings, Terminal Guidance] — yes/no

ATTRIBUTES (5+3 and 1+2)

- Government
  - Average Unit Procurement Price ($/unit), Adverse Weather Accuracy (mCEP), Aircraft Compatibility (num), Aircraft Carrier Operability (y/n), Retargeting Time (min), Warhead Compatibility (num), [Standoff Distance (nmi), Shelf Life (years), Clear Weather Enhanced Accuracy (mCEP)]
- Prime
  - Average Unit Cost ($/unit), [Average Unit Procurement Price ($/unit), Return on Investment (fraction)]

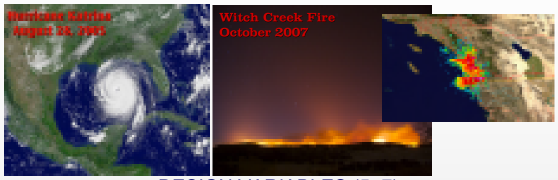
Rule-Effects Matrix			Design Variables											Path Enablers			Change Origin	
JDAM			Plf	NS	TS	GA	Sfw	PC		IC	LS	Wng	TG	Mod	COTS			
			DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV10	DV11	IV1	IV2	IV3	Flx	Adp
Rule	Refit strakes	R1	↑↓				↑↓	↑↓										
	Upgrade GPS	R2		↑↓			↑↓	↑↓										
	Upgrade INS	R3		↑↓			↑↓	↑↓										
	New software	R4					↑↓	↑↓										
	Refit for new AC	R5	↑↓				↑↓	↑↓										
	Refit for new Warhead	R6	↑↓	↑↓	↑↓		↑↓	↑↓										
	Replace tail section	R7	↑↓	↑↓			↑↓	↑↓										
		RK																
Potential Rules	Add IC	R8		↑↓	↑↓		↑↓	↑↓		±								
	Add LS	R9		↑↓	↑↓		↑↓	↑↓			±							
	Add wings	R10	↑↓				↑↓	↑↓				±						
	Add term guide	R11		↑↓	↑↓		↑↓	↑↓					±					

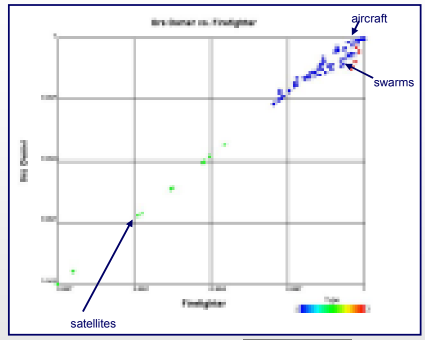
Number of Designs Explored: 7151

From Ross, 2006

Project 10: Disaster ORS

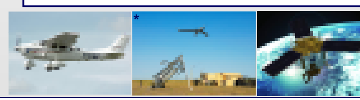
Multi-Concept Responsive Disaster Surveillance





DESIGN VARIABLES (5+7)

- Aircraft DV
  - Configuration Flag — 1-13 (3x jet, 2x small prop, 2x med UAV, small UAV, existing Cessna, Orion, Predator, ScanEagle, Global Hawk)
  - Gross Weight Flag — low, medium, high
  - Number of Assets — 1-6
  - Payload Type — visible, infrared
  - Aperture Size — 0.01, 0.02, 0.04, 0.07, 0.08 m
- Spacecraft DV
  - Deployment Strategy — 1-4 (on-orbit, launch-ready, pre-fab parts, classic design)
  - Altitude — 120-1100 km
  - Inclination — 0,23,90,sun-synch
  - Number of assets — 1-5
  - Payload Type — visible, infrared
  - Excess Delta-V — 600-1200 m/s
  - Ops Lifetime — 5-10 yrs



ATTRIBUTES (10): Firefighter/Owner

- Acquisition Cost ($M), Price/day ($K/day), Cost/day ($K/day), Responsiveness Time to IOC (days), Max % of AOI (%), Time to Max Coverage (min), Time between AOI (min), Imaging Capability (NIIRS level), Data Latency (min)

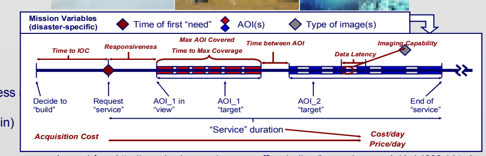
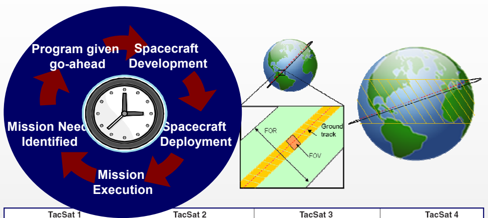


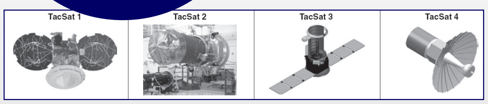
Image * from http://www.boeing.com/companyoffices/gallery/images/scaneagle/dvd-1390-1.html

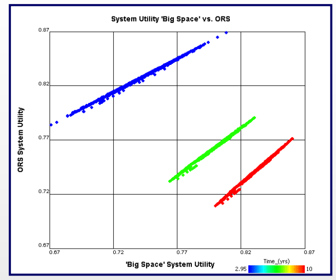
Number of Designs Explored: 2340+8640

Project 11: ORS

Paradigm flexibility assessed





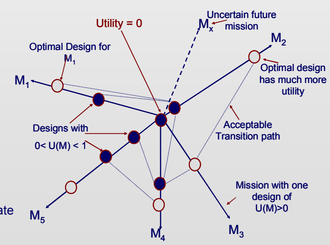


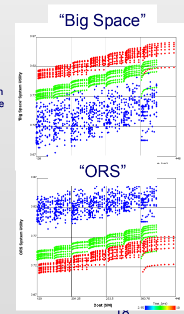
DESIGN VARIABLES (5)

- Orbit DV
  - Orbit Altitude 200-500 km
  - Orbit Inclination 20-90 degrees
- Spacecraft DV
  - Focal Length 0.5 – 2 m
  - Optic Sensitivity day and/or night
- Program DV
  - Desired Schedule 1 – 10 yrs

ATTRIBUTES (8)

- Signal Coverage (km2), Global Coverage (%), Resolution (m), Revisit Rate (days), Sensitivity (sensor type), Availability (%), Timeliness (years)

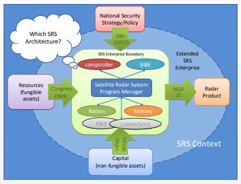




Number of Designs Explored: TBD

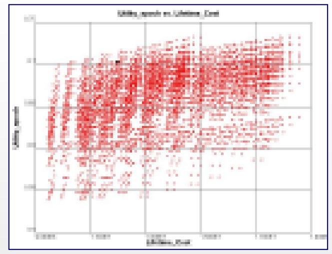
Project 12: SRS

Satellite-based radar multi-mission system of system



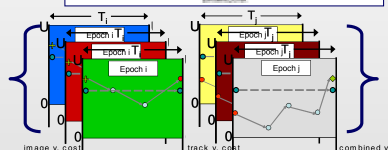
		ATTRIBUTES															
		Mission											Programmatics				
		Tracking						Imaging					Cost		Schedule		
Variable Name	Definition Range	Minimum Target RCS	Min. Discernable Velocity	Number of Target Boxes	Target ID Time	Target Track Life	Tracking Latency	Resolution (Proxy)	Targets per Pass	Field of Regard	Revisit Frequency	Imaging Latency	Baseline Cost	Actual Costs (Era)	Baseline Schedule	Actual Schedule (Era)	Total Impact
Peak Transmit Power	1.5 10 20 [KW]	9	9	9	3	1	1	9	9	9	0	1	9	9	9	9	96
Radar Bandwidth	.5 1 2 [GHz]	9	9	3	3	1	1	9	9	9	0	1	3	3	3	3	66
Physical Antenna Area	10 40 100 200 [m^2]	9	9	9	3	1	1	9	9	9	1	1	9	9	9	9	97
Antenna Type	Mechanical vs. AESA	9	9	9	3	3	1	9	9	9	1	1	9	9	9	9	99
Satellite Altitude	800 1200 1500 [km]	9	9	3	9	9	3	9	9	9	9	3	1	1	1	1	85
Constellation Type	8 Walker IDs	0	0	1	9	9	3	0	0	3	9	3	9	9	9	9	73
Comm. Downlink	Relay vs. Downlink	0	0	0	0	0	9	0	0	0	0	9	9	9	3	9	48
Tactical Downlink	Yes vs. No	0	0	0	0	3	9	0	0	0	0	9	9	9	3	9	51
Maneuver Package	1x, 2x, 4x	1	1	1	1	1	0	1	1	1	1	0	9	3	3	3	27
Constellation Option	none, long-lead, spare	0	0	0	0	0	0	0	0	0	0	0	9	9	9	9	36

(Row group label: DESIGN VARIABLES)



DESIGN VARIABLES (10)

- Orbit DV
  - Orbit Altitude — 800, 1200, 1500 km
  - Constellation design — 8 Walker IDs
- Spacecraft DV
  - Antenna Size — 40, 80, 100 m^2
  - Peak power — 1.5, 10, 20 kW
  - Radar bandwidth — 0.5, 1, 2 GHz
  - Comm Arch — relay, downlink
  - Tactical Downlink — yes/no
  - Path enablers — (Extra sats, fuel)

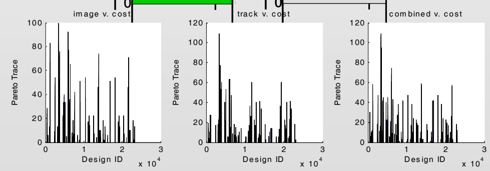


EPOCH VARIABLES (6)

- Technology avail, Comm infrastructure, Target list, AISR avail, Environment, Mission priorities

ATTRIBUTES (3 "missions", 15 total)

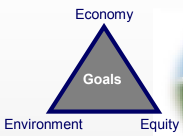
- Tracking, Imaging, Programmatic

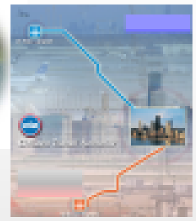


Number of Designs Explored: 23328; Number of Epochs Explored: 147

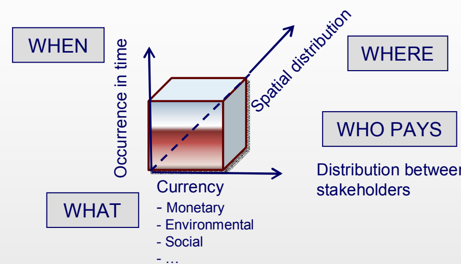
Project 13: High Speed Rail

Transportation system with multiple cost types

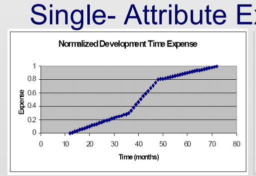


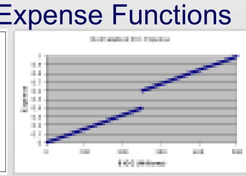


Different Cost Dimensions



Single- Attribute Expense Functions





Diller, N.P., Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirements, 2002

DESIGN VARIABLES (TBD)

ATTRIBUTES (TBD)

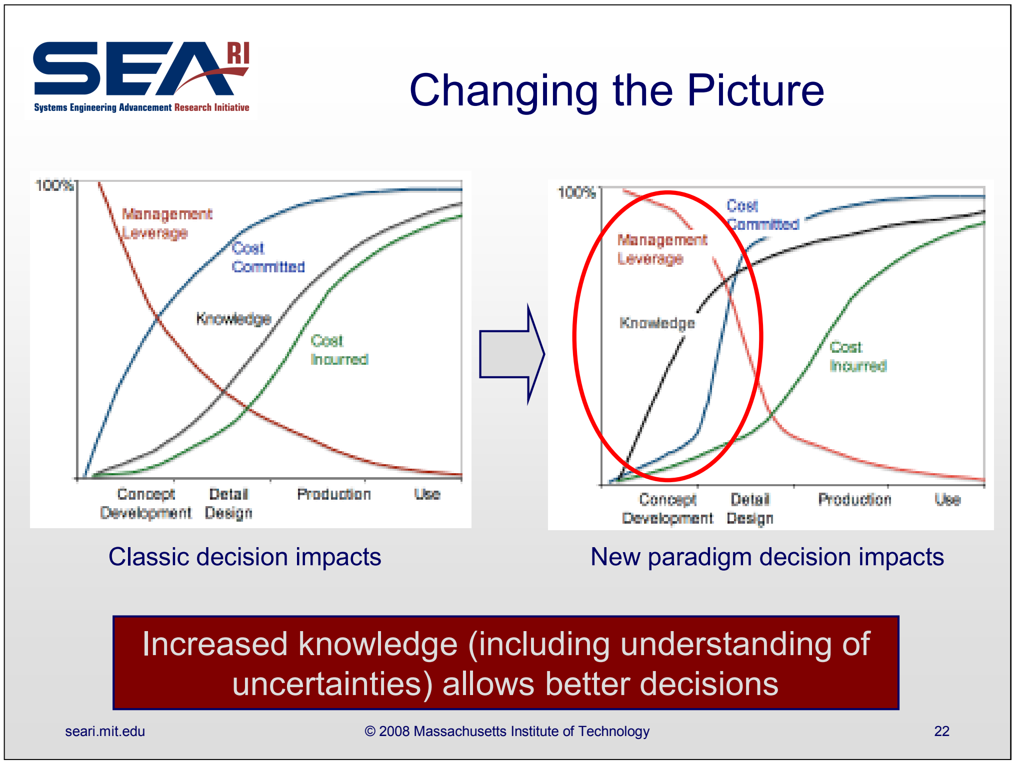
Number of Designs Explored: TBD

Characteristics of Multi-Attribute Tradespace Exploration

A process for understanding complex solutions to complex problems

- Model-based high-level assessment of system capability
- Ideally, *many* alternatives assessed
- Can compare heterogeneous, new and old concepts on common basis
- 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
- Can serve as a boundary object for communicating desires and technical feasibility

Enhances knowledge for "upfront" decision-making and planning



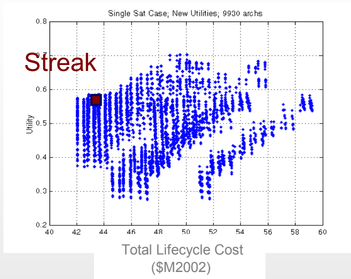
This is a chart students may have seen before. The point is, upfront activity CONSUMES very little money, but COMMITS a great deal, and changes from these early decisions gets harder and hard to do (and more and more expensive!). So we want to do up-front work, and make upfront decisions, right.

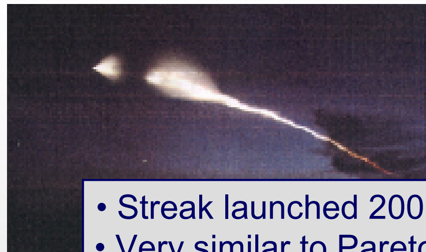
But (not on chart) UNCERTAINTY Is very high early in the program, so how can good decisions be made?

Systems Engineering Advancement Research Initiative

Back up

Streak - Successful System





- Streak launched 2005
- Very similar to Pareto X-TOS design

X-TOS vs. Streak

	XTOS (2002 study)	Streak (Oct 2005 launch)
Wet Mass kg	325 - 450	420
Lifetime (yrs)	2.3 - 0.5	1
Orbit	300 -185 km @ 20°	321a-296p -> 200 @ 96°
Launch Vehicle	Minotaur	Minotaur
Utility	0.61 - 0.55	0.57 - 0.54*
Modified Utility**	0.56 - 0.50	0.59
Cost $M	75 - 72	75***
Instruments	Three (?)	"Ion gauge and atomic oxygen sensor"

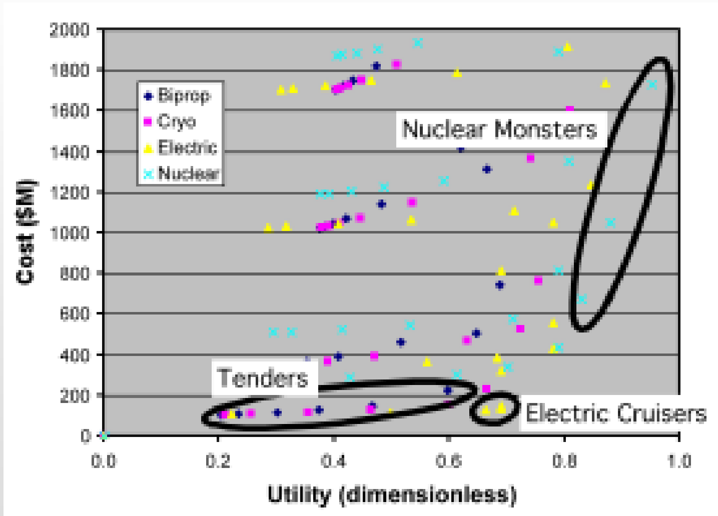
Extra fuel allowed orbit changes to increase value

Inclination different
A user preference for data at the terminator unexpressed at time of X-TOS

Streak values from information in published sources (Aviation Week)
*Calculated with X-TOS preferences
**Modified to account for changed preferences
***Estimate using X-TOS model

SpaceTug: General Survey

Finding designs that *may* interest various customers

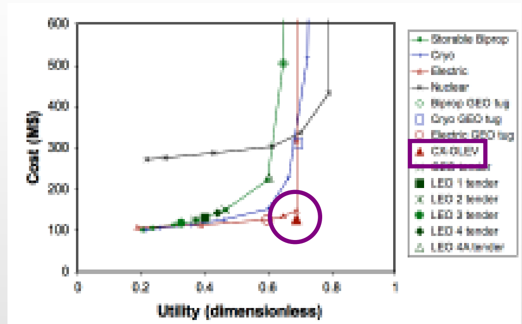


Full Scale Development of an Electric Cruiser: Orbital Recovery Corp.

Orbital Recovery Corp.

“Orbital tugboat” to supply propulsion, navigation and guidance to maintain a satellite in its orbital slot for 10+ years

CX-OLEV values from information in published sources (ORC website)
*Back-calculated using models
,*Accounts for changed assumption on ISP



	Electric Cruiser (2002 study)	CX-SLES (2009 launch)
Wet Mass kg	1405	1400
Dry Mass kg	805	670*
Propellant kg	600	730*
Equipment kg	300	213*
DV m/s	12000 – 16500***	15900**
Utility	0.69	0.69
Cost	148	130*

seari.mit.edu

26

ESA public-private partnership

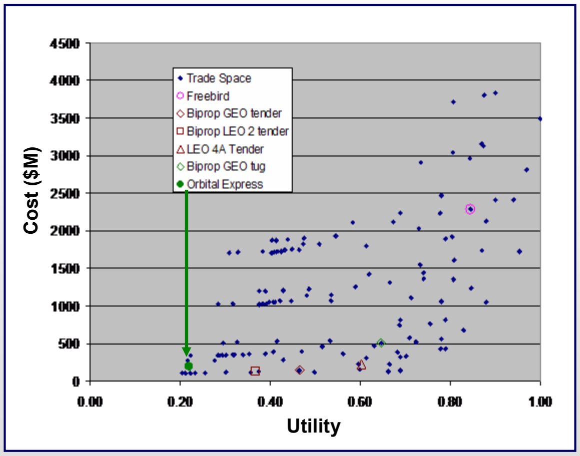
Dock with the apogee kick stage nozzle

Light enough for secondary payload on EELV or emerging low-cost LVs

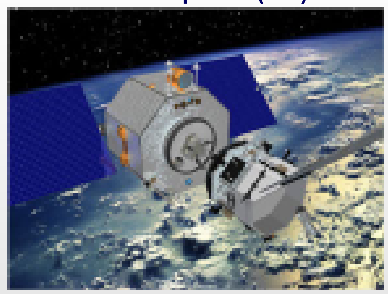
Identified 130 GEO comsats as potential targets

Entered into memo of understanding

Orbital Express: An Experimental Tender



Orbital Express (OE)



On-orbit validation of autonomous docking, refueling, component swapping; focus on non-proprietary interfaces

Flown 2007