Presented at the 2008 SCEA-ISPA Joint Annual Conference and Training Workshop - www.iceaaonline.com

estimate

estimate • analyze • plan • control

SEER for Hardware's Cost Model for Future Orbital Concepts ("FAR OUT")

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ISPA/SCEA Industry Hills 2008

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Introduction

A model for predicting the cost of long term unmanned orbital spacecraft (Far Out) has been developed at the request of AFRL.

Far Out has been integrated into SEER for Hardware.

This presentation discusses the Far Out project and resulting model.

Goals

- Estimate space satellites in any earth orbit. Deep space exploration missions may be considered as data is available, or may be an area for further research in Phase 3.
- Estimate concepts to be launched 10-20 years into the future.
- Cost missions ranging from exploratory to strategic, with a specific range decided based on estimating reliability. The most reliable estimates are likely to be in the middle of this range.
- Estimates will include hardware, software, systems engineering, and production.
- Handle either government or commercial missions, either "one-of-a-kind" or constellations.
- Be used in a "top-down" manner using relatively less specific mission resumes, similar to those available from sources such as the Earth Observation Portal or Janes Space Directory.

Challenge: Technology Change Over Time

Evolution in bus technologies

1. Propulsion
   a) Chemical
   b) Electric
   c) Solar, nuclear, microwave
2. Thermal Control
   a) Passive systems, including multi-layer insulation, radiators.
   b) Active systems, including heat pipes and coolers
   c) Future exotic systems, including micro electromechanical system (MEMS) cooling, smart materials and new coatings
3. Structures
   a) Aluminum
   b) Composite
   c) Control-structures interaction and smart structures
4. Electrical Power
   a) Solar cells, with accompanying growth in efficiency over time
   b) Nuclear
   c) Solar concentrators, solar dynamic systems (Stirling, etc.)
5. Downlink frequency and associated Antenna and Pointing Requirements
   a) Growth in frequency over time, from S- through C, K and X bands
   b) Phased arrays
   c) Laser communications
   d) Algorithmic improvements, including multiple access protocols, compression, etc.
6. Computational
   a) Improvements in speed, memory
   b) Increased availability of COTS hardware and software
   c) High levels of automation, self learning and correcting
   d) Optical computers
7. On-Orbit Data Storage
   a) Tape Recorders
   b) Solid State Recorders
   c) Future Systems

Evolution in payload technologies and performance

1. Payload Pointing Sensitivity
   a) Pointing accuracy requirements
   b) Pointing knowledge requirements
   c) Fraction of Arc Second requirement decrease over time
   d) Target resolution (meter resolution, target size)
2. Payload Data Rate Requirements over time
   a) Track the total data rate of the instrument complement
   b) Track the peak data rate
   c) Track total bits per day
3. Aperture
   a) Mirror or reflector size.
      i) 1970 = ~1 meter
      ii) 1990 = ~ 2.4 meter (Hubble)
      iii) 2010 = ~ 6 meter (James Webb Space Telescope)
      iv) Beyond 2015 = ~ 100 meter (inflatable films)
   b) Mirror or reflector technology
      i) Ground glass
      ii) Ground exotic material
      iii) Thin material shaped on-orbit
      iv) Inflatable
      v) Other exotic
4. Station Keeping Requirement (knowledge)
   a) 1970 Kilometers
   b) 1990 Meters (GPS)
   c) 2010 Nanometers (LISA)

Guiding Hypothesis

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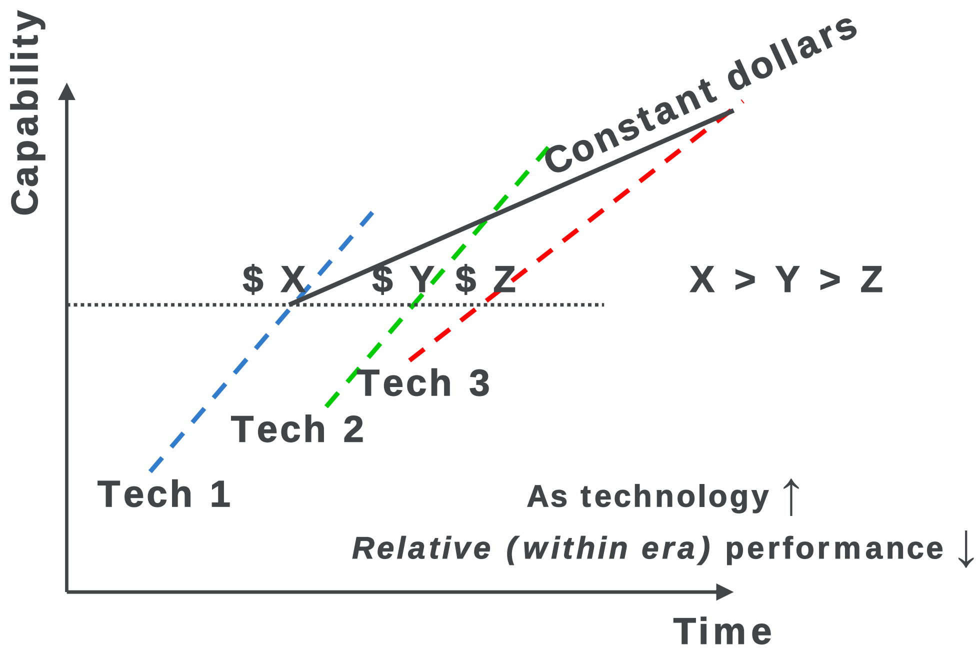
As Technologies Evolve Discontinuously,
The Cost Envelope Evolves Deterministically



Team

- Lee Fischman – Project management and model creation. Senior Director of Development Galorath.
- Mike Kimel – Assistance with statistical modeling. Previous positions in telecomm, corporate economics, academia, and hedge funds, Mike is now with First Energy Corp. Ph.D. in Economics from UCLA.
- Dave Pine (NASA, Ret.) – Data provisioning and analysis. Senior NASA executive previously responsible for major program cost analysis and evaluation. From 1988-90, Deputy Program Manager (telescope operations and science support) for the Hubble Space Telescope.
- Troy Masters – System designer / programmer.
- Dale Martin (Maj. USAF, Ret.) – Data collection and collation. Previously held mgmt. positions in costing at USAF Space and Missiles Center.


Data and Modeling
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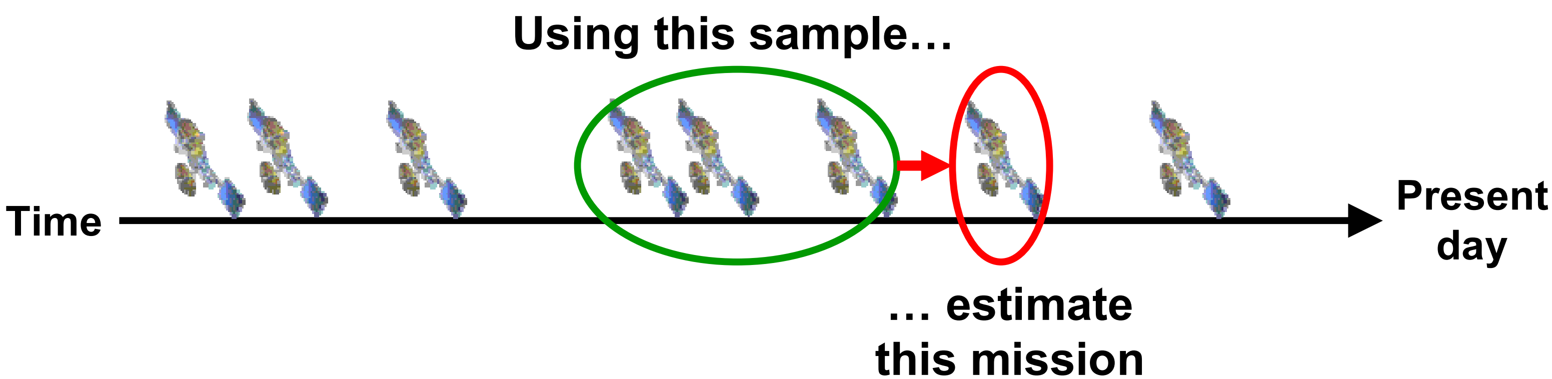
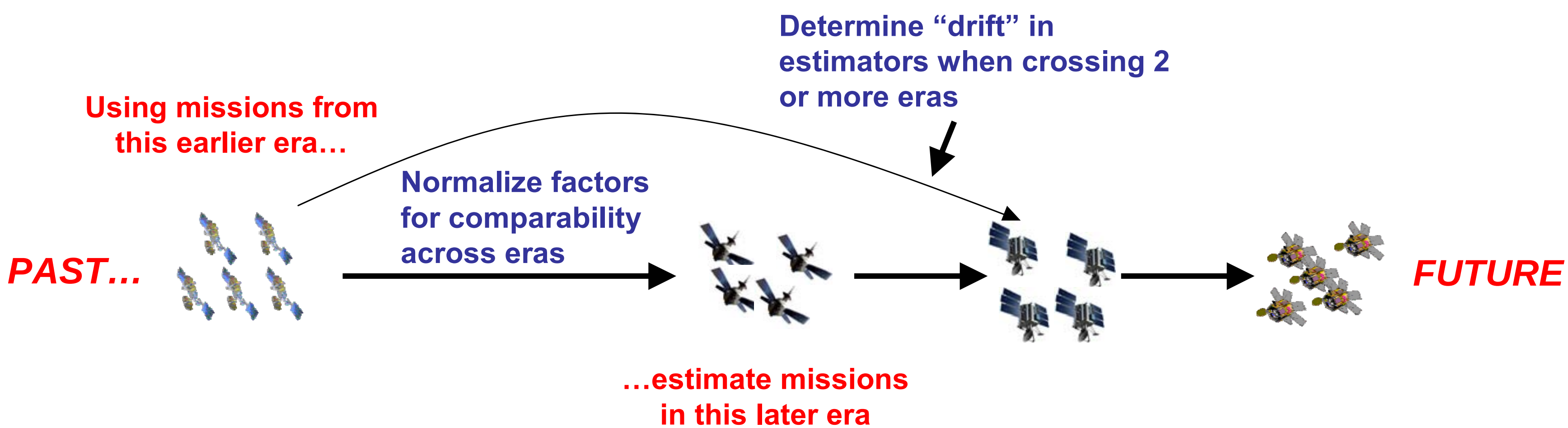
Basic Approach:
Time- Windowed Calibration and Test





Primary Data Sources

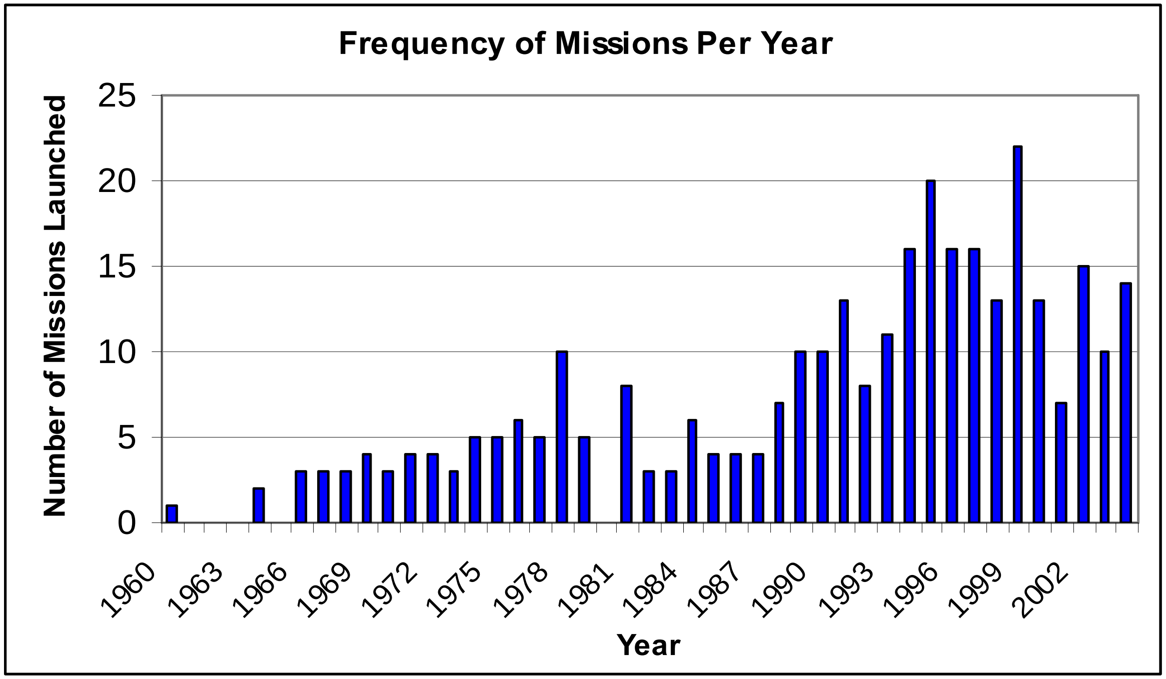
- NASA Air Force Cost Model – carefully collated on a narrow range of missions.
- NASA – Hard to get information (cost!) on a large variety of missions; specially collected.
- Janes (commercial) – Exhaustive narratives on large number of missions.
- The Satellite Encyclopedia – Online catalogue at www.tbs-satellite.com/tse/online/index.shtml
- Earth Observation Portal (ESA) – Basic info on missions at directory.eoportal.org/res_p1_Satellitemission.html

- 200+ missions
- From late 60s through 2005
- Military, government and commercial missions.
- Mission level information (power, stabilization, # of sensors, etc) being used.

Missions In Database

ACE (Advanced Composition Explorer)	IMP-H (Interplanetary Monitoring Platform)	STEP0 (Space test Experiment Platfor	Acrimsat (Active Cavity Radiometer Irradiance Mo
ACTS (Advanced Communications Technolog	INTELSAT-III (International Telecommunica	STEP1 (Space test Experiment Platfor	AMSC-1
AE-3 (Atmospheric Explorer)	INTELSAT-IV (International Telecommunica	STEP3 (Space test Experiment Platfor	Aurora 2
AMPTE-CCE (Active Magnetospheric Particle	JWST (James Webb Space Telescope)	STEREO (Solar Terrestrial Relations C	CALIPSO (Cloud-Aerosol Lidar & Infrared Pathfin
Aqua (Latin For Water)	KEPLER	Surveyor	Calipso (Picasso)
ATS-1 (Applications Technology Satellite)	LANDSAT-1	SWAS (Submillimeter Wave Astronom	CHIPS (Cosmic Hot Interstellar Plasma Spectrom
ATS-2 (Applications Technology Satellite)	LANDSAT-4	TACSAT (Tactical Communications Sa	Columbia 5 (CommSat)
ATS-5 (Applications Technology Satellite)	LANDSAT-7	TDRSS (Tracking Data Relay Satellite	DBS-1
ATS-6 (Applications Technology Satellite)	Lewis	TDRS F7	Deep Space 2 (DS-2) [2 Probes] [Probes Piggyba
AURA	Lunar Orbiter	TDRS F7	DSCS 3 F7 (DSCS III)
Cassini Spacecraft + Huygens Probe	Lunar Prospector	TDRS (Next Generation) I,J &K (8,9,&1	EchoStar 5
Cassini	Magellan	TDRS (Next Generation)	EUVE (Extreme Ultraviolet Explorer)
Chandra X Ray Observatory(AXAF)	WMAP (Wilkinson Microwave Anisotropy Pr	Terra (Latin for "Land") [Also known as	Galaxy 11
Clark [Cancelled due to cost overrun]	Mariner-4	TIMED (Thermosphere, Ionosphere, M	Galaxy 5
Clementine	Mariner-6	TIROS-M (Television Infrared Observa	GE 5
CloudSat [dual launch with Calipso]	Mariner-8	TIROS-N (Television Infrared Observa	GOES 3 (Geostationary Operational Environment
COBE (Cosmic Background Exploer)	Mariner-10	TOMS-EP Total Ozone Mapping Spect	GOES 9
Contour (Comet Nucleus Tour)	MARISAT	TOPEX (The Ocean Topography Expe	GOES N
CRRES (Combined Release and Radiation Ef	Mars Express/Beagle 2	TRMM (Tropical Rain Measuring Missi	GStar 4
Dawn	Mars Global Surveyor	UARS (Upper Atmosphere Research S	HESSI-II
DE-1 (Dynamics Explorer)	Mars Observer	UFO (UHF Follow On)	Ikonos
DE-2 (Dynamics Explorer)	Mars Odyssey [Mars Surveyor 2001 Orbiter]	VELA-IV	Inmarsat 3-F5
Deep Impact Flyby Spacecraft & Impactor	Mars Pathfinder & Sojourner Rovers	Viking Lander (Two Landers but cost &	Intelsat K
Deep Space 1 (DS-1)[Includes 2 Probes--see	MCO (Mars Climate Orbiter) [One of two pro	Viking Orbiter (Two Orbiters but cost a	IUE (International Ultraviolet Explorer)
DMSP-5D (Defense Meteorlogical Satellite Pr	(MRO) Mars Reconnaissance Orbiter	Voyager [Two Spacecraft but cost and	Jason 1
DMSP-5D3 (Defense Meteorlogical Satellite F	Mars Polar Lander [One of two projects whic	MSX (Mid-course Space Experiment)	Landsat 3
DSCS-II (Defense Satellite Communicatins Sy	MER (Mars Exploration Rover) [Two Rovers	QuikSCAT	Landsat 4
DSCS-IIIA (Defense Satellite Communicatins	Messenger (Mercury Surface, Space Enviro	QuikSCAT	Mars Telecommunication Orbiter (MTO)
DSCS-IIIB (Defense Satellite Communicatins	Model-35	GFO 1	Meteor
DSP (Defense Support Program)	NATO III	Argos	NIMBUS
Earth Observing 1 (EO-1)	NEAR (Near Earth Asteroid Rendezvous) [re	Iridium	Polar
ERBS (Earth Radiation Budget Experiment)	New Horizons	NOAA 15	Rosetta Instruments
FLTSATCOM 6(Fleet Satellite Communicatio	NPP (NPOESS Preparatory Project)	Globalstar 8	Sage III (the third Stratospheric Aerosol and Gas
FUSE (Far Ultraviolet Spectroscopic Explorer	OCO (Orbiting Carbon Observatory)	orbcomm	Seastar
GALEX (Galaxy Evolution Explorer)	OSO-8 (Orbiting Solar Observatory)	orbview 2	SMM (Solar Maximum Mission)
Galileo Orbiter & Probe	P78	Step m4	Swift (Gamma Ray Burst Explorer)
Genesis (including sample return capsule)	Phoenix	Milstar 3 / Adv. EHF	Terriers
GLAST (Gamma Ray Large Area Space Tele	Phoenix	JAWSAT	Tethered Satellite System (TSS)
GPS-1 (Global Positioning Satellite)	Pioneer Venus Bus/Orbiter, Small Probe an	Pas 4	TRACE (Transition Region and Coronal Explorer)
GPS-IIR (Global Positioning Satellite)	Pioneer-10	SBS 5	Triana
GPSMYP (Global Positioning Satellite)	RHESSI (Reuven High Energy Solar Spectro	UFO 4	Ulysses
GRACE (Gravity Recovery and Climate Exper	S3 (Space Test Program Small Secondary S	UFO 9	Vegetation Canopy Lidar (VCL) [Cancelled due to
Gravity Probe-B (GP-B)	SAMPEX (Solar Anomalous and Magnetosp	DSCS 3 F10	Wind
GRO/Compton Gamma Ray Observatory	SCATHA (Spacecraft Charging at High Altitu	Satcom C3	WIRE (Wide-Field Infrared Explorer)
HEAO-1 (High Energy Astronomical Observat	Spitzer Space Telescope (formerly SIRTF-S	Satcom C4	XTE (X-ray Timing Explorer, RXTE)
HEAO-2 (High Energy Astronomical Observat	SME (Solar Mesosphere Explorer)	Orion 1	HETE-II (High Energy Transient Explorer)
HEAO-3 (High Energy Astronomical Observat	SMS-1 (Synchronous Meterological Satellite	STRV 1D	DART (Demonstration For Autonomous Rendezv
HST (Hubble Space Telescope) [SSM&OTA]	Solar Dynamics Observatory	Anik E1	OMV
ICESat (Ice, Clouds, and Land Elevation Sate	SORCE (Solar Radiation and Climate Exper	Anik E2	XSS-11
DSCS I (IDCSP/A)	SIM (Space Interferometry Mission)	Morelos	TSX-5
IMAGE (Imager for Magnetopause to Aurora (	Stardust & Sample Return Capsule	NOAA 8	XSS-10
			DSX

Data Collection Chronologic Summary



Modeling Approaches Attempted

- Coefficient trend determination through static models and stepwise regression
- Complexity index by automatically weighted inputs
- Complexity index by analogy
- Neural networks
- Automated windowed coefficient trending
- Boosting using binomial logit classifiers
- Weighted combinations of simple models

Underlying Model - Neural Network

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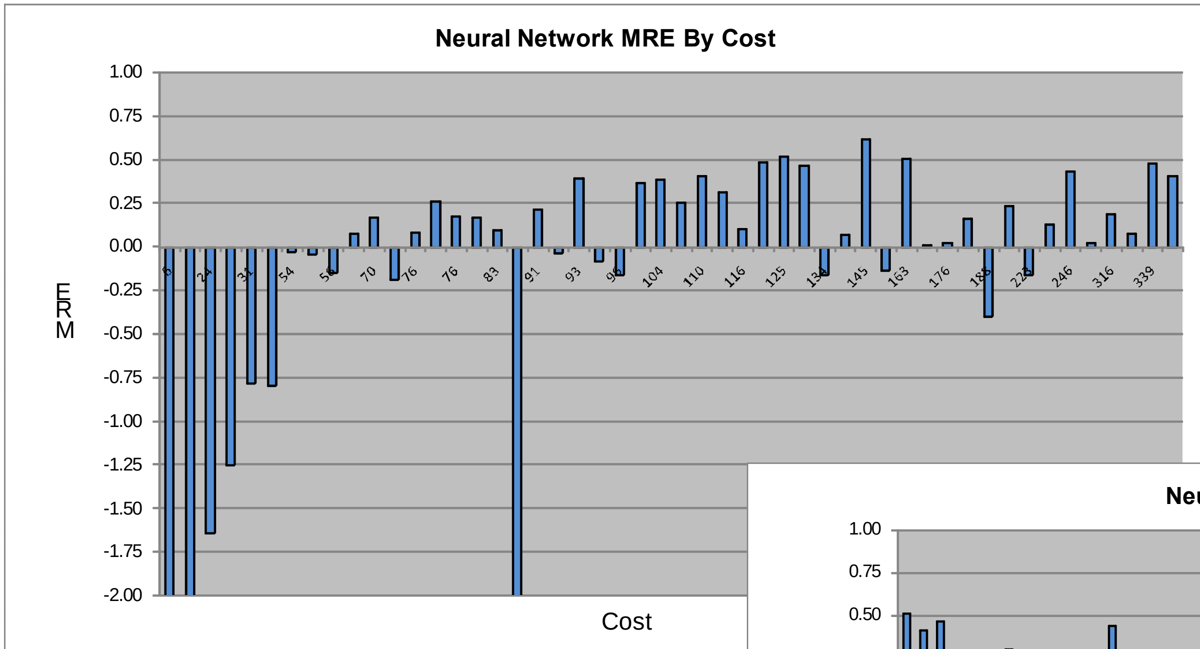
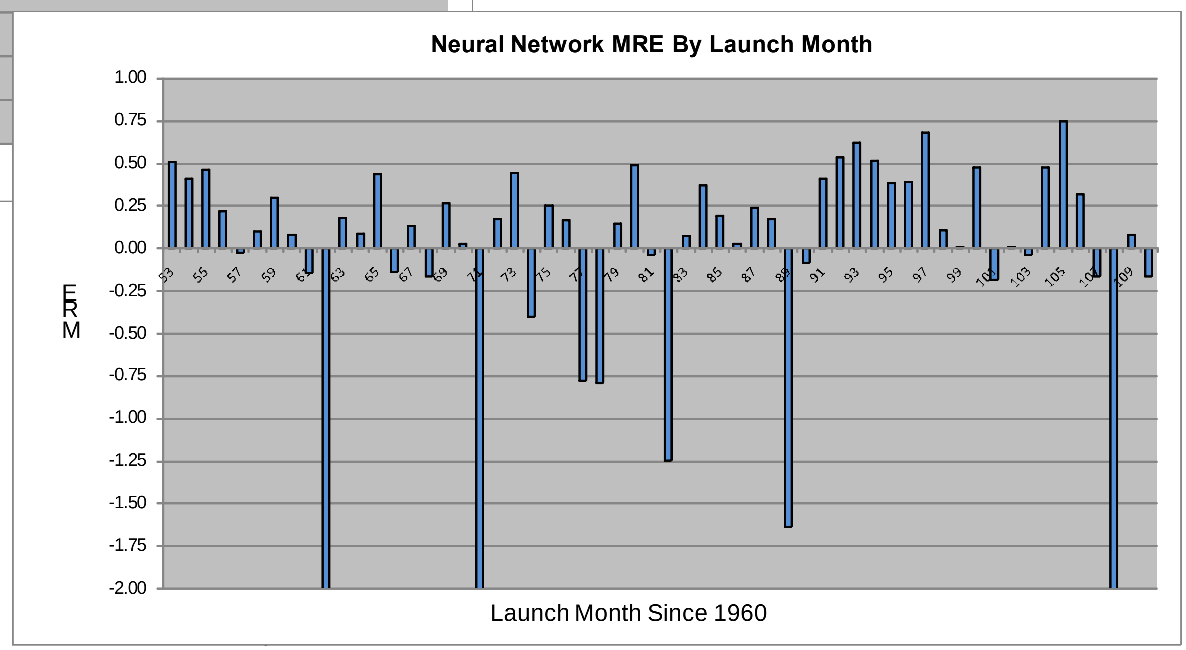


Neural networks normally seem better suited to "interpolative" applications such as classification, including pattern recognition, or function approximation. They may tend to over-fit and so an important step we took was in normalizing our data, essentially converting it from an extrapolative problem to an interpolative one. The normalization we undertook was transforming each field to its percentage rank vis-a-vis the observed minimum and maximum for that factor. For example, a design life of 24 months might lie in the 25th percentile for all observed design life, and so on.

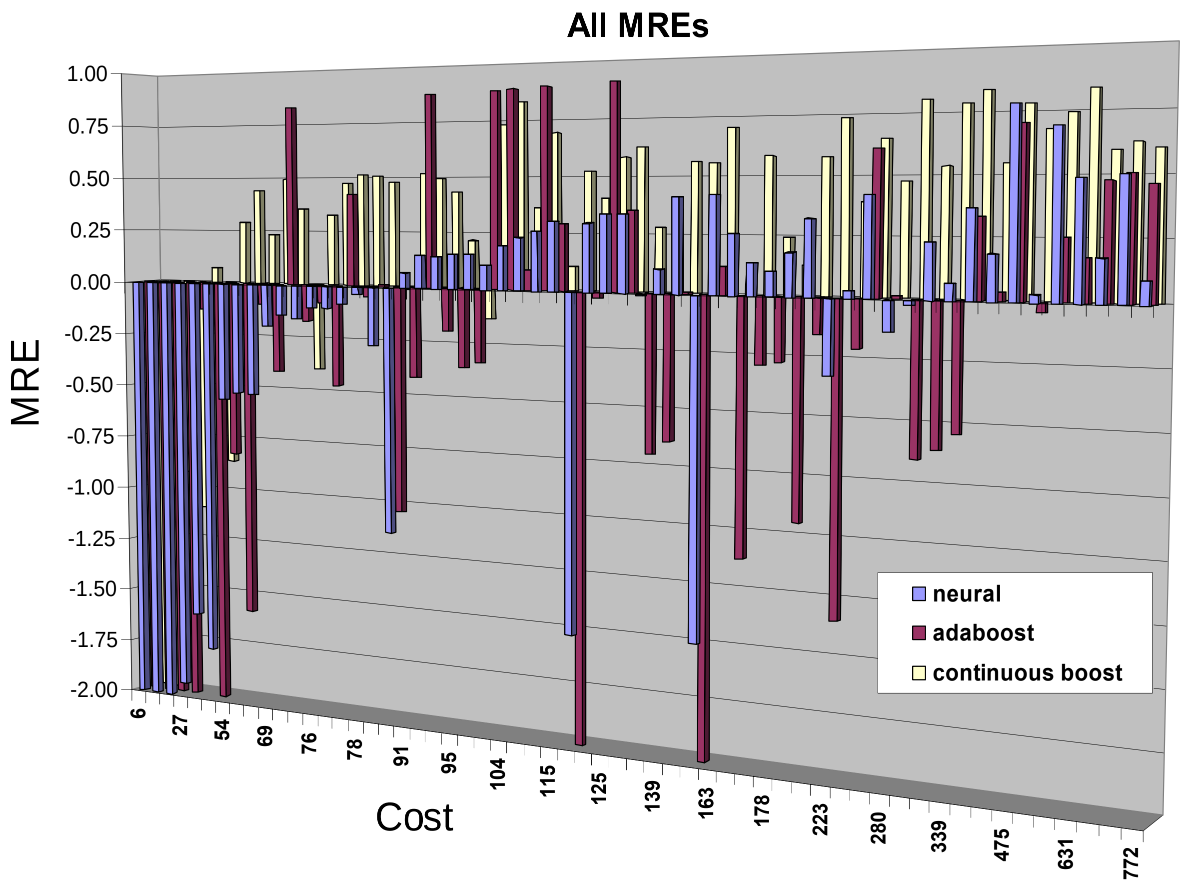
Training was carried out using 52 missions from the 1960s through 1996 and testing occurred on 58 missions from 1996 through 2007.

Sorted chronologically, virtually no degradation in accuracy can be seen as estimates go farther out, up to 11 years. This was good news for being able predict future missions, and may have been due to our normalization process, which basically embedded the effect of time within the factors being input to the model.



Comparison of Leading Results

<u>The neural network performs best, followed by Adaboost and then continuous boosting.</u> This judgment is based on a relative comparison of estimates; it can be seen that neural network estimates are regularly closer to zero deviation between estimated and actual cost. It is interesting to note that in the three instances where the neural network predicts too low by a substantial margin also correspond to worst performances for the Adaboost method, pointing to exceptional data points.



Supporting Analyses

Influence of Programmatic Factors

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Program	Program Redesign	Technical Complexity	Budget Constraint	Incomplete Estimate	Challenger Delay	Inflation Effect
TETHER		+		+	+	
XTE	+			+		
GALILEO	+	+			+	+
AXAF	+	+	+	+		+
ATP	+	+				+
HST		+		+	+	+
EUVE	+			+		
GOES I-M	+	+				+
AFE	+		+	+		
GRO		+	+		+	+
ASRM	+	+	+			+
NSCAT	+					+
MARS OBS.	+	+	+		+	+
OMV	+	+	+			+
TDRS-7		+	+	+		
LANDSAT-D	+	+				+
COSTR	+					
TRMM	+			+	+	
ULYSSES	-		+	+	+	
MAGELLAN	+	+				
FTS	-	+		+	+	+
ACTS	+		+			+
TOPEX		+				
FREEDOM	+	+	+			+
GGS			+			
UARS					+	
CASSINI	-		+	+		+
ENDEAVOUR						
EOS	-					+

Linear regression

Regression Statistics	
Multiple R	0.60
R Square	0.36
Adjusted R Square	0.19
Standard Error	90.79
Observations	29.00

	Coefficients	*Standard Error*	*t Stat*
Intercept	29.41	45.27	0.65
Program Redesign	22.40	45.24	0.50
Technical Complexit	87.09	39.94	2.18
Budget Constraint	-47.82	35.81	-1.34
Incomplete Estimate	82.86	39.22	2.11
Challenger Delay	16.94	40.61	0.42
Inflation Effect	-19.30	46.35	-0.42

Log transformed cost

Regression Statistics	
Multiple R	0.58
R Square	0.34
Adjusted R Square	0.16
Standard Error	0.44
Observations	29.00

	Coefficients	*Standard Error*	*t Stat*
Intercept	1.58	0.22	7.18
Program Redesign	0.24	0.22	1.07
Technical Complexit	0.53	0.19	2.73
Budget Constraint	0.03	0.17	0.20
Incomplete Estimate	0.25	0.19	1.32
Challenger Delay	0.12	0.20	0.62
Inflation Effect	-0.31	0.22	-1.36

Log transformed zero intercept

Regression Statistics	
Multiple R	0.94
R Square	0.89
Adjusted R Square	0.82
Standard Error	0.79
Observations	29.00

	Coefficients	*Standard Error*	*t Stat*
Intercept	0.00	#N/A	#N/A
Program Redesign	1.21	0.31	3.90
Technical Complexit	1.09	0.32	3.44
Budget Constraint	0.37	0.30	1.25
Incomplete Estimate	0.54	0.33	1.64
Challenger Delay	0.55	0.34	1.63
Inflation Effect	-0.38	0.40	-0.94

Schedule As A Function of Project Launch Era

	Project Develop. Duration (Months)	ATP-PDR Time (Months)	PDR-CDR Time (Months)	CDR-1st Flight Time (Months)	ATP-PDR Time by %	PDR-CDR Time by %	CDR-1st Flight Time by %
Major Projects - Pre-1980	73	25.9	14.2	33.0	32.8%	19.8%	47.4%
Moderate Projects - Pre-1980	59	20.2	11.4	27.2	34.3%	20.7%	45.0%
Minor Projects - Pre-1980	41	9.1	11.8	20.5	21.8%	29.8%	48.4%
	======	======					
	57.8	18.4					
Major Projects - Post-1980	104	16.8	28.2	58.8	16.7%	27.2%	56.1%
Moderate Projects - Post-1980	71	14.9	13.3	42.4	20.4%	20.1%	59.5%
Minor Projects - Post-1980	45	7.5	9.6	32.0	14.6%	19.5%	65.9%
	======	======					
	73.2	13.1					

The data show that regardless of the size of the project, the projects after 1980 have nearly 30% less time allocated from ATP to PDR. They also on average took about 27% longer to accomplish. One might conclude that the rush to start projects has resulted in longer total development times, a premise to which I whole-heartedly subscribe.

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Schedule As A Function of Project Duration And Scope

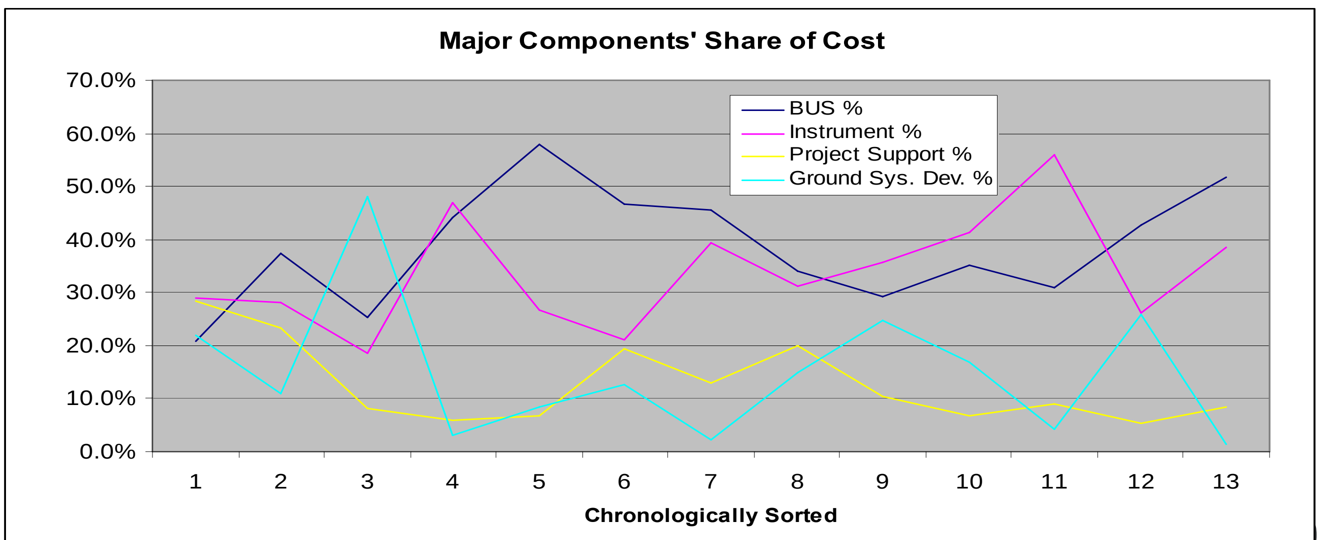
1=Major 2=Moderate 3=Minor Project	Project Develop. Duration (yrs)	Project Develop. Duration (Months)	ATP-PDR Time (Months)	PDR-CDR Time (Months)	CDR-1st Flight Time (Months)	ATP-PDR Time by %	PDR-CDR Time by %	CDR-1st Flight Time by %
Overall Schedule Length								
Less than 3.5 Years	2.2	26.3	3.7	8.5	14.0	14.5%	32.0%	53.5%
3.5 years to less than 5 years	4.2	50.7	10.8	10.8	29.1	21.5%	21.2%	57.3%
5 years to 6.5 years	5.7	68.8	13.7	16.8	38.4	20.1%	24.0%	55.9%
Greater than 6.5 years	8.1	97.7	26.4	18.8	52.5	28.5%	19.0%	52.5%

Regardless of the length of the schedule, the time from CDR to first launch averages 55% of the total project development time +/- 2.5%.
On the other hand, the longer the total development time the higher the percent of time from ATP-PDR and conversely the shorter the time from PDR to CDR.

Project Develop. Duration (yrs)	Project Develop. Duration (Months)	ATP-PDR Time (Months)	PDR-CDR Time (Months)	CDR-1st Flight Time (Months)	ATP-PDR Time by %	PDR-CDR Time by %	CDR-1st Flight Time by %
Major	84	19.6178	21.1689	43.4	23.2%	24.7%	52.1%
Moderate	66	16.0	13.2	37.3	23.9%	21.2%	54.8%
Minor	45	8.2	10.56	26.68	18.0%	24.1%	57.9%
GRAND TOTAL AVG - All Missions	62	13.6147	14.0938	34.35593	21.3%	23.3%	55.4%

Project major elements

date	PROJECT	Total Cost at Time of Data	BUS	Instrument	Project Support	Ground Sys. Dev.	BUS %	Instrument %	Project Support %	Ground Sys. Dev. %
6/1/1989	12-Defense Support Prog. - D	$8,111.0	$1,678.0	$2,355.0	$2,295.0	$1,783.0	20.7%	29.0%	28.3%	22.0%
2/1/1996	Near Earth Asteroid Rendez.	$109.7	$41.1	$30.8	$25.7	$12.1	37.5%	28.1%	23.4%	11.0%
11/1/1996	Mars Global Surveyor	$274.7	$69.6	$50.9	$22.2	$132.0	25.3%	18.5%	8.1%	48.1%
8/1/1997	ACE	$106.8	$47.0	$50.2	$6.3	$3.3	44.0%	47.0%	5.9%	3.1%
10/1/1997	Cassini	$1,190.0	$690.0	$319.0	$79.0	$102.0	58.0%	26.8%	6.6%	8.6%
11/1/1997	TRMM	$238.5	$111.5	$50.5	$46.4	$30.1	46.8%	21.2%	19.5%	12.6%
5/13/1998	NOAA (K-N')	$1,036.0	$471.0	$408.0	$135.0	$22.0	45.5%	39.4%	13.0%	2.1%
12/1/2001	TIMED	$122.8	$41.6	$38.4	$24.4	$18.4	33.9%	31.3%	19.9%	15.0%
1/1/2003	Icesat	$188.3	$55.0	$67.3	$19.5	$46.5	29.2%	35.7%	10.4%	24.7%
8/1/2003	SIRTF	$512.0	$179.4	$212.0	$34.5	$86.1	35.0%	41.4%	6.7%	16.8%
4/1/2004	Gravity Probe - B	$425.6	$131.1	$237.7	$38.8	$18.0	30.8%	55.9%	9.1%	4.2%
10/5/2006	STEREO	$229.0	$98.0	$60.0	$12.0	$59.0	42.8%	26.2%	5.2%	25.8%
2/1/2009	POES	$1,133.8	$586.4	$437.9	$95.0	$14.5	51.7%	38.6%	8.4%	1.3%



Far Out Model In SEER for Hardware

SEER for Hardware Interface

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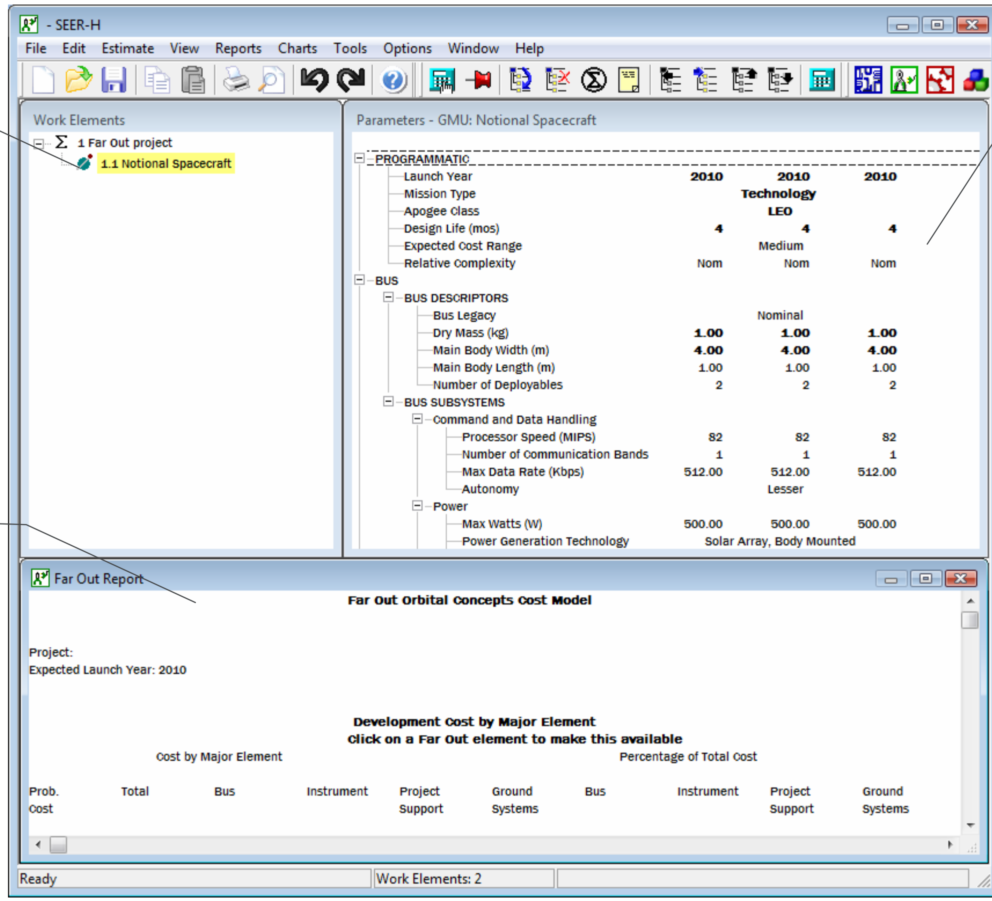
WBS View

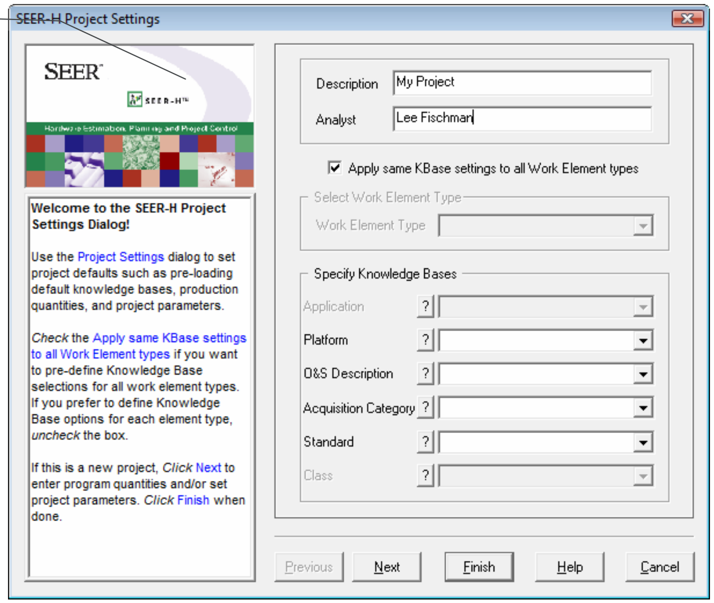
Parameter Entry

Reports and Charts View; One Far Out report is available

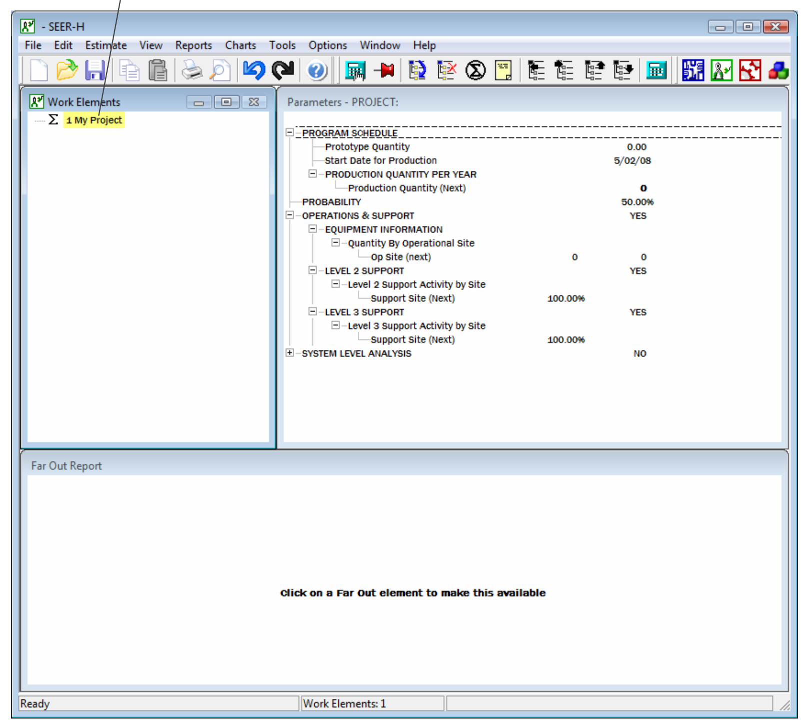


First Action – Create A New Project

New Project Dialog

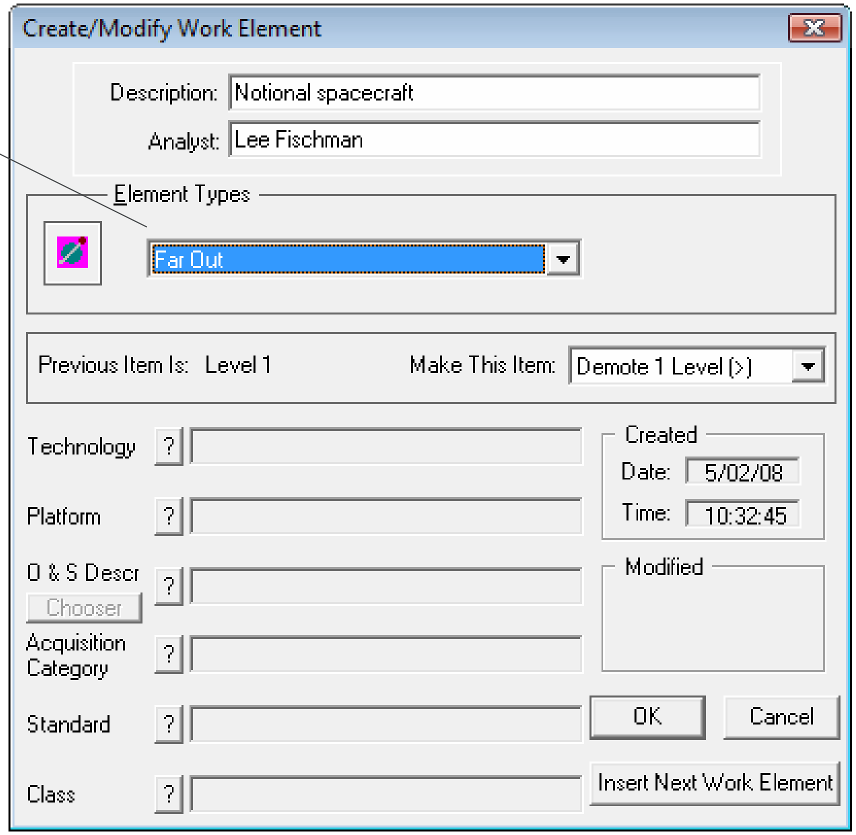


A new Project element (Elements must be created below)



Next Create A Far Out Element

Far Out Element is selected from the Element Type list



Far Out Entry Screen

Parameters - GMU: Notional Spacecraft

Parameter	2010	2015	2020
PROGRAMMATIC			
Launch Year	**2010**	**2015**	**2020**
Mission Type		Comm	
Apogee Class		HEO/GEO	
Design Life (mos)	24	24	24
Expected Cost Range		Medium	
Relative Complexity	Nom	Nom	Nom
BUS			
BUS DESCRIPTORS			
Bus Legacy		Nominal	
Dry Mass (kg)	498.05	498.05	498.05
Main Body Width (m)	1.00	1.00	1.00
Main Body Length (m)	1.00	1.00	1.00
Number of Deployables	2	2	2
BUS SUBSYSTEMS			
Command and Data Handling			
Processor Speed (MIPS)	82	82	82
Number of Communication Bands	1	1	1
Max Data Rate (Kbps)	512.00	512.00	512.00
Autonomy		Lesser	
Power			
Max Watts (W)	500.00	500.00	500.00
Power Generation Technology		Solar Array, Body Mounted	
Solar Array Technology		SiGaAs	
Solar Array Output (watts/kg)	**150**	**150**	**150**
Attitude Control and Determination			
Pointing Accuracy	0.36	0.36	0.36
Thermal Technology		Detector Coolers	
INSTRUMENTS			
Number of Instruments	3	3	3
Payload Legacy		Nominal	

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Far Out Report

Far Out Orbital Concepts Cost Model

Project: Notional Spacecraft
Expected Launch Year: 2015

Development Cost by Major Element

	Cost by Major Element					Percentage of Total Cost			
Prob. Cost	Total	Bus	Instrument	Project Support	Ground Systems	Bus	Instrument	Project Support	Ground Systems
10%	78,653,356	38,429,860	27,452,301	11,011,484	1,759,712	48.9%	34.9%	14.0%	2.2%
20%	82,031,000	40,080,170	28,631,196	11,484,354	1,835,280	48.9%	34.9%	14.0%	2.2%
30%	83,533,545	40,814,310	29,155,628	11,694,711	1,868,896	48.9%	34.9%	14.0%	2.2%
40%	84,937,256	41,500,160	29,645,564	11,891,231	1,900,301	48.9			
50%	86,058,406	42,047,952	30,036,878	12,048,192	1,925,385	48.9			
60%	86,736,101	42,379,072	30,273,413	12,143,069	1,940,547	48.9			
70%	87,793,386	42,895,659	30,642,436	12,291,089	1,964,201	48.9			
80%	88,738,592	43,357,485	30,972,340	12,423,418	1,985,349	48.9			
90%	90,520,915	44,228,324	31,594,423	12,672,944	2,025,224	48.9			

Development Cost by Phase

	Cost by Major Element				Percentage of Total Cost		
Prob. Prob.	Total	ATP-PDR	PDR-CDR	CDR-1st Flight	ATP-PDR	PDR-CDR	CDR-1st Flight
10%	78,653,356	27,591,690	32,450,529	18,611,138	35.1%	41.3%	23.7%
20%	82,031,000	28,776,571	33,844,065	19,410,363	35.1%	41.3%	23.7%
30%	83,533,545	29,303,666	34,463,980	19,765,899	35.1%	41.3%	23.7%
40%	84,937,256	29,796,089	35,043,118	20,098,048	35.1%	41.3%	23.7%
50%	86,058,406	30,189,390	35,505,678	20,363,338	35.1%	41.3%	23.7%
60%	86,736,101	30,427,126	35,785,279	20,523,695	35.1%	41.3%	23.7%
70%	87,793,386	30,798,023	36,221,490	20,773,872	35.1%	41.3%	23.7%
80%	88,738,592	31,129,603	36,611,460	20,997,529	35.1%	41.3%	23.7%
90%	90,520,915	31,754,844	37,346,805	21,419,267	35.1%	41.3%	23.7%

Far Out Report (Continued)

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Development Duration by Phase

	Total Duration		Duration by Major Phase			Percentage of Total Duration		
Prob. Dur	Years	Months	ATP-PDR	PDR-CDR PDR-CDR	CDR-1st Flight	ATP-PDR	PDR-CDR	CDR-1st Flight
10%	3.6	44	5	8	30	11.1%	19.3%	69.6%
20%	3.6	44	5	8	30	11.1%	19.3%	69.6%
30%	3.7	44	5	8	30	11.1%	19.3%	69.6%
40%	3.7	44	5	8	31	11.1%	19.3%	69.6%
50%	3.7	44	5	8	31	11.1%	19.3%	69.6%
60%	3.7	44	5	8	31	11.1%	19.3%	69.6%
70%	3.7	44	5	9	31	11.1%	19.3%	69.6%
80%	3.7	44	5	9	31	11.1%	19.3%	69.6%
90%	3.7	44	5	9	31	11.1%	19.3%	69.6%

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Parameter Sensitivity

Notional system

Parameters - GMU: Notional spacecraft

Parameter			
PROGRAMMATIC			
Launch Year	2008	2008	2008
Mission Type		Comm	
Apogee Class		HEO/GEO	
Design Life (mos)	24	24	24
Expected Cost Range		Medium	
Relative Complexity	Nom	Nom	
BUS			
BUS DESCRIPTORS			
Bus Legacy		Nominal	
Dry Mass (kg)	498.05	498.05	
Main Body Width (m)	1.00	1.00	
Main Body Length (m)	1.00	1.00	
Number of Deployables	2	2	
BUS SUBSYSTEMS			
Command and Data Handling			
Processor Speed (MIPS)	82	82	
Number of Communication Bands	1	1	
Max Data Rate (Kbps)	512.00	512.00	
Autonomy		Lesser	
Power			
Max Watts (W)	500.00	500.00	
Power Generation Technology		Solar Array, Body Mounted	
Solar Array Technology		SiGaAs	
Solar Array Output (watts/kg)	0	0	
Attitude Control and Determination			
Pointing Accuracy	0.36	0.36	
Thermal Technology		Detector Coolers	
INSTRUMENTS			
Number of Instruments	3	3	3
Payload Legacy		Nominal	

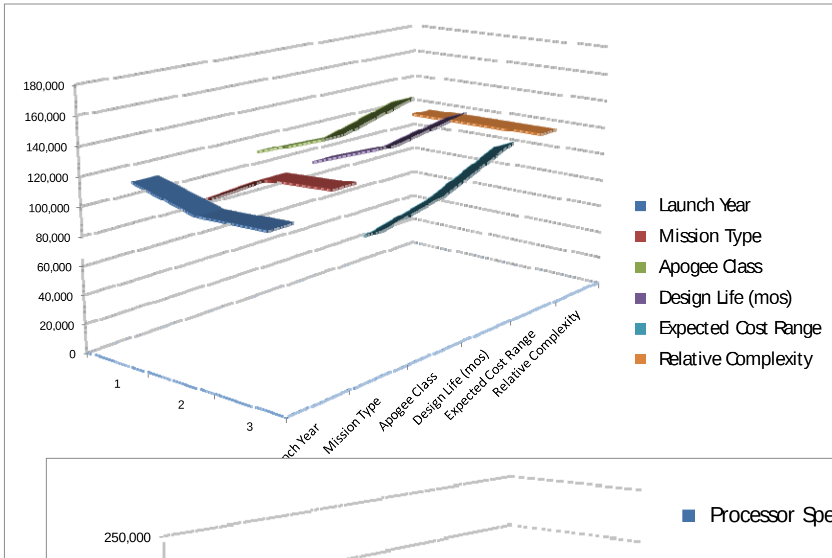
Development Cost by Major Element
You must enter data for 'Launch Year'

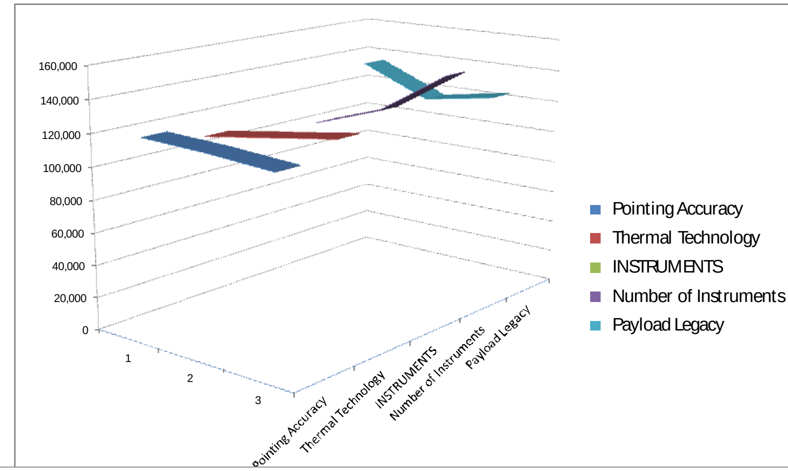
	Cost by Major Element					Percentage of Total Cost			
Prob. Cost	Total	Bus	Instrument	Project Support	Ground Systems	Bus	Instrument	Project Support	Ground Systems
10%	119,943,665	58,603,405	41,863,815	16,792,945	2,683,500	48.9%	34.9%	14.0%	2.2%
20%	120,246,033	58,751,140	41,969,350	16,835,278	2,690,264	48.9%	34.9%	14.0%	2.2%
30%	120,518,404	58,884,218	42,064,416	16,873,412	2,696,358	48.9%	34.9%	14.0%	2.2%
40%	120,679,780	58,963,065	42,120,740	16,896,006	2,699,969	48.9%	34.9%	14.0%	2.2%
50%	120,892,521	59,067,008	42,194,993	16,925,791	2,704,728	48.9%	34.9%	14.0%	2.2%
60%	121,116,746	59,176,563	42,273,254	16,957,184	2,709,745	48.9%	34.9%	14.0%	2.2%
70%	121,358,570	59,294,715	42,357,658	16,991,041	2,715,155	48.9%	34.9%	14.0%	2.2%
80%	121,642,872	59,433,623	42,456,887	17,030,846	2,721,516	48.9%	34.9%	14.0%	2.2%
90%	122,015,476	59,615,674	42,586,937	17,083,013	2,729,852	48.9%	34.9%	14.0%	2.2%

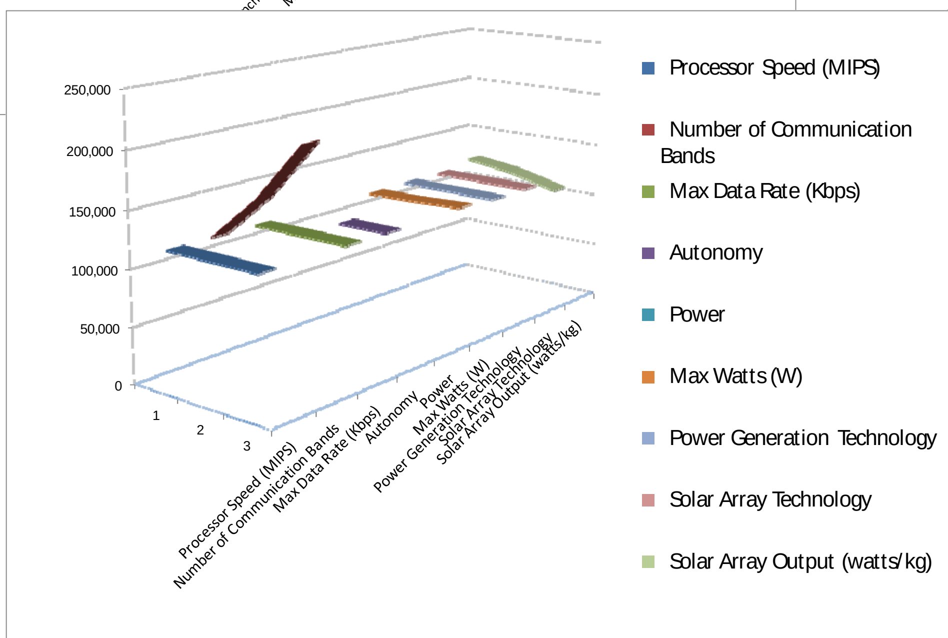
Parameters' Relative Effect

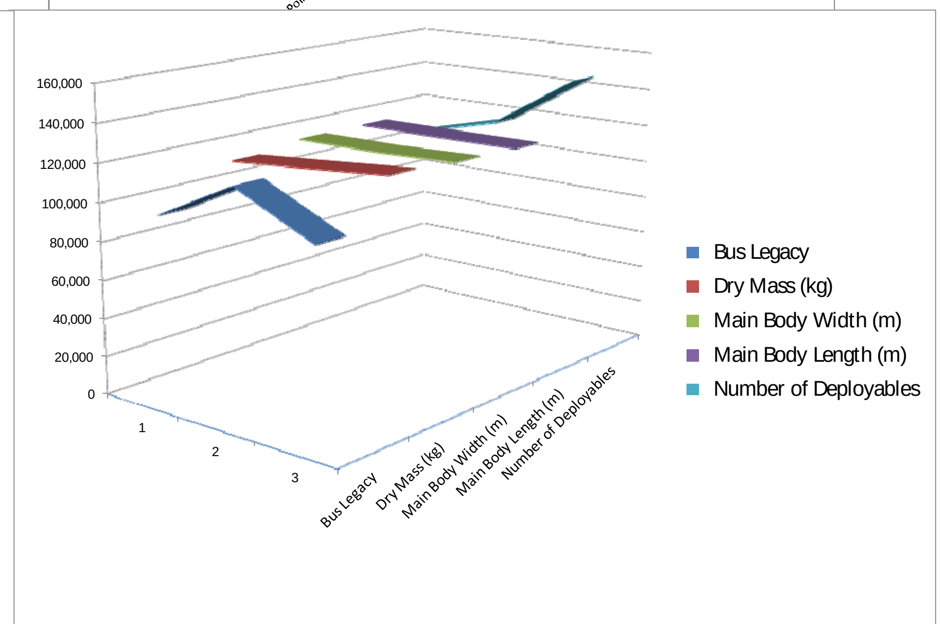
					Range of Settings			
PROGRAMMATIC								
Launch Year	117,234	104333	105,822		2008	2015	2022	
Mission Type	93,073	117,234	119,804		Technology	Comm	Sensing	
Apogee Class	117,234	133,897	166,260		HEO/GEO	Leo	Planetary	
Design Life (mos)	100,066	117,234	146,948		6	24	48	
Expected Cost Range	31192	68,812	117,234	142,787	Smallest	Small	Medium	Large
Relative Complexity	117,234	117,234	117,234		Vlo	Nom	Vhi	
BUS								
BUS DESCRIPTORS								
Bus Legacy	95,014	117,234	97,566		Minor	Nominal	Extensive	
Dry Mass (kg)	113,665	117,234	121,040		200	498.05	800	
Main Body Width (m)	117,161	117,234	118,706		0.5	1	4	
Main Body Length (m)	117,185	117,234	117,525		0.5	1	4	
Number of Deployables	105,801	117,234	146,233		0.5	2	4	
BUS SUBSYSTEMS								
Command and Data Handling								
Processor Speed (MIPS)	117,247	117,234	117,203		50	82	160	
Number of Communication Bands	117,234	157,775	211,066		1	3	5	
Max Data Rate (Kbps)	117,220	117,234	117,314		256	512	2048	
Autonomy		117,234	117,234			Lesser	Greater	
Power								
Max Watts (W)	116,381	117,234	119,259		200	500	1200	
Power Generation Technology	117,234	117,234	117,234		n/a	n/a	n/a	
Solar Array Technology	117,234	117,234	117,234		n/a	n/a	n/a	
Solar Array Output (watts/kg)	123,377	117,234	106,275		0	46	92	
Attitude Control and Determination								
Pointing Accuracy	118,740	117,234	114,392		0.18	0.36	0.72	
Thermal Technology	110,667	117,234	123,605		Radiators a	Detector C	Miniaturized MEMS cooler	
INSTRUMENTS								
Number of Instruments	102,545	117,234	145,431		1	3	6	
Payload Legacy	135,390	117,234	124,556		Minor	Nominal	Extensive	

Parameter Effects Graphically









Programmatic Parameters 1

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PROGRAMMATIC

This is a parameter category which contains parameters describing the general nature of the project:

Launch Year

The year when the project will be launched. A project may consist of several units, block purchases, or options consisting of several units within each block or option purchase. For a multi-unit project, enter the year of launch of the first unit. For a block/ option project (e.g., a specific unit used as an analog), enter the year of launch of the first unit of that build.

Mission Type

Select the Mission Type that most closely describes the main purpose of the mission. A project may also fly payloads of opportunity (based on space available), which have little to do with the main mission. The Mission Type, however, refers only to the main purpose, not these ancillary objectives.

Item	Description
Technology	A technical test of a satellite.
Comm	Communication missions relay domestic or military transmissions, such as telephone, radio, and TV signals, from one point on the Earth's surface to another.
Sensing	Sensing missions gather information about natural phenomena or human activities on Earth or other planets, or in space.

Programmatic Parameters 2

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Apogee Class

Select the orbital requirement that most closely matches the mission. The nature and objectives of the mission will determine the most advantageous orbit.

Item	Description
LEO	Low Earth Orbit, with apogees and perigees below 3,000 km.
HEO/GEO	High Earth, Highly Elliptical, and Geosynchronous orbits. GEO orbits are used by communication and weather satellites, with apogees between 30,000 km and 40,000 km. For a geostationary orbit, an altitude of about 36,000 km is needed.
Planetary	Missions to a different body – another planet or moon, a comet, etc.

Design Life

The required lifetime for the mission. A longer Design Lifetime requires more robust systems. This parameter directly impacts the level of redundancy in the design and the cost of system design and implementation, since more hardware will be required, and will be cross-strapped to provide greater redundancy. It also affects Integration and Test.

Note that this parameter represents the required, rather than the expected, lifetime; many satellites operate well past their design lifetime.

Programmatic Parameters 3

Expected Cost Range

Based on the first unit's cost from Authority To Proceed (ATP) through launch of the first unit. These costs include development of the ground systems, but not launch vehicle or operations costs.

The Expected Cost Range parameter directs the model to the proper set of Cost Estimating Relationships (CER's) and is especially important in estimating schedule lengths.

Item	Definition
Smallest	Up to $50,000,000.00 (US).
Small	Between $50,000,000.00 and $175,000,000.00.
Medium	Between $175,000,000.00 and $716,000,000.00.
Large	Greater than $716,000,000.00.

Programmatic Parameters 4

Relative Complexity

Use this parameter only when you have very little concrete information about the project and are looking for a ballpark estimate of cost and schedule.

Use the sliders to select the Least (lowest likely), Likely (most likely), and Most (highest likely) levels of complexity.

Item	Description
VHi	Most technologies will be decidedly difficult to accomplish given the anticipated state of the art.
Hi	Most technologies will be harder to accomplish given the anticipated state of the art.
Nom	Technologies will be no harder nor simpler to accomplish than most other missions of the time.
Lo	Most technologies will be straightforward to accomplish given the anticipated state of the art.
VLo	All technologies will be trivial to accomplish given the anticipated state of the art.

Bus Descriptors Parameters 1

BUS DESCRIPTORS

This is a category parameter. Note that NASA uses the term *Bus* while the DoD uses the term *spacecraft* for the same set of subsystems. NASA uses the terms *spacecraft*, *satellite* or *observatory* to mean the entire flight article (bus + payload). DoD uses *space vehicle* to describe the entire flight article. Both agencies use the terms *payload* or *instruments* for the sensors that perform objective of the mission interchangeably.

Bus Legacy

How much of the bus consists of legacy hardware and design. Take into account the level of modifications that will likely be requested. Commercial missions may use standard busses with little or no modification. Government missions, however, are more likely to require major modifications; DoD requirements for radiation hardening, long-life redundancy and encryption may negate much of the savings from using a high legacy bus.

Government projects often operate at the cutting-edge of technology, and developing bus subsystems that can support such high-tech payloads can necessitate modifications that are beyond existing or expected in the near future heritage systems. It is even possible that trying to force-fit a long list of modifications into an existing commercial bus could cost more than building a new bus from scratch.

Item	Description
Extensive	Based in large part on past designs.
Nominal	Borrowing from past designs with significant amounts of new design.
Minor	Predominantly new design, perhaps with reference to known designs and technology.

Bus Descriptors Parameters 2

Dry Mass

The expected weight (when completed), in kilograms, including contingencies, of the satellite on Earth, excluding the launch vehicle adaptor and fairing weight, and upper stages if they are not an integral part of the satellite. Exclude the weight of fuels, oxidizers and pressurants but includes the weight of the tanks holding the liquids. For example, an apogee kick motor that is released from the space vehicle stack after completing its role would not count as space vehicle mass, whereas an internal liquid propulsion system doing the same job would be.

Main Body Width

The longest width of the space vehicle measured in the direction of the pitch axis, in meters, after all deployables have been activated.

Main Body Length

The longest measurement lengthwise of the space vehicle measured in the direction of the roll axis, in meters, after all deployables have been activated.

Number of Deployables

Deployables are space vehicle components which are folded and latched for launch, then deployed after the space vehicle is separated from the launch vehicle protective hardware, or later. Enter the total number of items deployed; if, for example, the solar array has two wings, enter two deployables, because there are two distinct deployment systems. However, each fold of a wing would not be a deployable.

Typical deployables include solar arrays and the antenna systems, as well as payload elements requiring deployment, thermal control elements, telescope covers, etc.

Bus Subsystems C&DH Params 1

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Command and Data Handling

This is a category parameter. The computer, C&DH, and telemetry systems are the heart of any spacecraft bus and their proper performance is central to accomplishment of the mission. The C&DH subsystem controls the operation of other elements of the space vehicle. It sends commands to the elements and receives data from them, processing data to ensure that they are working properly. The communications portion of the C&DH system sends telemetry data to ground operators and receives commands for the operation of the space vehicle. The selection of correct model input parameter values determines both whether requirements will be met and the cost of meeting those requirements. This model examines four parameters to characterize the C&DH system.

Processor Speed

Processor Speed is the rate at which the selected flight computer executes operational instructions, measured in Millions of Instructions per Second (MIPS). After a spacecraft design is determined, a suitable computer must be matched to it. The individual subsystems and programs required to run on the computer dictate how much power, in the computing sense, a processor will need. Accurate scaling is vital to the design on the command system. Too few MIPS and a computer will be unable to run the spacecraft, while too many and the computer will be wasting power and money. Processor speed has be increasing dramatically for decades, and predictions are that it will continue. The model has already extrapolated this technology tread and will assess individual requirements against the likelihood of availability of the technology when needed. Space application processor speed lags terrestrial because of the severe environment of space and the need to have fully tested, high reliability chips. Over the past thirty years space application chip MIPS have increase from .4 MIPS to between 240 and 300 MIPS.

Bus Subsystems C&DH Params 2

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Number of Communication Bands

There are a number of radio frequency ranges in use in satellite communications, such as C, L, S, X, Ku, and Ka-band. Satellite-to-satellite communication at light wave frequencies is also an option. The higher the frequency, the more data (bits) that can be carried on that communication link. The Number of Communication Bands dictates the number of transmitters, receivers, or transponders, the number and types of antennas and impacts to the power, C&DH and Attitude Control & Determination subsystems. Since Number of Communication Bands is a significant design driver, this parameter also becomes a significant cost driver.

Maximum Data Rate

The maximum downlink rate from the space vehicle to the ground in Kbps (kilobits per second). The communications subsystem uses transmitters, receivers or transponders - a transmitter and receiver in one component, to handle all transmit (telemetry) and receive (command) communications functions. The digital bit rate for uplinks (ground to space vehicle), downlinks (space vehicle to ground) or payload and housekeeping data that is transmitted is the Data Rate for that element. In designing the various subsystems the Data Rate drives the selection of communication bands, antenna types and sizes, transmit power requirements, fields of view, allowable data error rates, etc.

Bus Subsystems C&DH Params 3

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Autonomy

Select Greater or Lesser Autonomy.

Item	Description
Greater	Select Greater Autonomy if the space vehicle is capable of routinely carrying out most or all of the functions for which it was designed without receiving instructions from the ground. A highly autonomous device can receive non-routine instructions from the ground for some purposes, including emergency override commands or (in the case of planetary exploration devices) mission direction/ redirection instructions, but under most circumstances, it will not need such commands. In the case of a highly autonomous planetary exploration vehicle, for example, new mission instructions would come from a ground station, but the device itself would make most or all of the decisions required to navigate around obstacles and determine the details of the path to a new location, as well as automatically taking samples when it arrives.
Lesser	Select Lesser Autonomy if the space vehicle requires ground instructions for a significant portion of its routine tasks. In general, if a vehicle does not fit the description of Greater Autonomy, select Lesser. For passive or near-passive devices (such as transponders) or those with very simple functions, Autonomy should be set to Lesser, even if they ordinarily operate without ground instructions.

Bus Subsystems Power Params 1

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Power

This is a category parameter. Space power systems are on-board assemblages of equipment to generate, store, and distribute electrical energy on satellites/ spacecraft. A reliable source of electrical power is required for supplying energy to the spacecraft and its payloads during launch and through its years of operational lifetime in a space environment.

Power generation in most cases is by solar arrays, although fuel cells are used by the Space Shuttle and any vehicle going further than the orbit of Mars must use a method that excludes converting solar energy.

Max Watts

Enter the maximum power in watts which the vehicle will require. The maximum power requirement for a space vehicle is the greatest amount of power that the space vehicle requires. The maximum power requirement can, for a short period, be greater than what is provided by the power generation system, as that power can be supplemented by power stored by the batteries. However, for an orbit the power generation system must be able to power all required space vehicle systems and recharge the power storage system or the power system will run at a deficit and discharge, threatening the vehicle. Many factors influence the final configuration of a power system. Basic to the initial consideration are the nature of the mission (Earth-orbiting or planetary) and mission lifetime. Other relevant factors include (1) spacecraft and payload requirements with consideration to average and peak power loads; (2) effect of environment such as orbit period, length of time the spacecraft is in sunlight and shadow, radiation particle damage, and space charging; and (3) constraints imposed by the spacecraft such as weight, volume, spacecraft shape and appendages, satellite attitude control, electromagnetic radiation limitations, characteristics of payloads, and thermal dissipation.

Bus Subsystems Power Params 2

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Power Generation Technology

This selection details the means by which power will obtained. Power either may be generated on-board or, if a short mission, stored prior to launch using batteries. Deep space missions going away from the sun sometimes rely on a radioisotope thermoelectric generator, as the energy of the sun is increasingly insufficient as a distance from it increases.

Item	Description
Solar Array, Body Mounted	
Solar Array, Deployed	
RTG	Radioisotope thermal generator.
Batteries	Any type of battery technology.
Other	Relying on external power, exotic sources, etc.

Solar Array Technology

Select the solar array technology to be used on the mission.

Item	Description
Si	Silicon
SiGaAs	Silicon Gallium Arsenide
GaAs on Ge	Gallium Arsenide on Geranium
High Efficiency SiGaAs	Improved efficiency Silicon Gallium Arsenide
Multi-Junction GaAs	Highly efficent technology using multiple thin films.
Si-Indium Phosphide on Ge	Silicon Indium Phosphide on Geranium

Bus Subsystems Attitude Control Params

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Solar Array Output

Solar Array Output requirements are measured in how many watts per kilogram the power generation system produces. Solar arrays are becoming more efficient, producing more electricity for the same area of solar array, and also becoming lighter so that they allow more of the system weight to be used by the payload. Systems projected for the future include solar concentrator arrays, where sunlight is concentrated and reflected onto boilers that in turn produce electricity, rather than using photovoltaic systems. Such systems could provide more than an order of magnitude improvement in watts/ kg over current systems.

Attitude Control & Determ. Parms

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Attitude Control and Determination

This is a category parameter. Attitude Control and Determination has two distinct parts that must work together in order that a space vehicle can successfully complete its mission.

1. Attitude control is that part of Attitude Control and Determination that physically moves the satellite to a desired position and holds it there so that the space vehicle can complete its functions. There are many different attitude control systems that the designer can select among, to

2. Attitude determination is that part of Attitude Control and Determination that tells the control system how much to alter the space vehicle's attitude, tracks the changes in attitude, marking the precise attitude for transmission to the ground. The direction the satellite is pointing is

Pointing Accuracy

Enter the pointing accuracy in degrees. Pointing Accuracy or the ability for the space vehicle's attitude to be control such that the payload can complete its objectives is a mission requirement that is generated by the needs of the payload instrumentation. Pointing Accuracy is a major design driver; it determines how sensitive the space vehicle must be to its own mechanical forces like vibrations and moving appendages. It is important to ensure that physical distortions do not affect Pointing Accuracy, so this parameter impacts the mechanical alignment of the attitude control system with the payloads as well as thermal stability. Pointing Accuracy can be a function of the entire satellite or of an individual instrument, once the satellite points the instrument relatively close to its target. Some instruments can change their observation direction by commands sent from the earth or under spacecraft autonomous control.

Bus Subsystems Thermal Params

Thermal Technology

Select the thermal technology system from the list. The thermal system regulates the temperature of the satellite's components. Too hot or too cold, or too great a swing in temperature will prematurely end the useful life of a satellite. The thermal system dissipates the heat into space. Temperatures are controlled within acceptable temperature ranges for all subsystems, including the payload. There are two types of thermal control: passive control which depends on passive materials or devices such as surface treatments, heat pipes, radiators and dewars, and active control which depends on active devices such as electric coolers and heaters.

The Thermal Technology system required is dependent upon the temperatures needed by the mission and the amount of mass that needs that temperature. Some payloads require that only the detector (measured in grams) be cooled, whereas others require that the entire instrument be cooled (measured in kilograms), and sometimes even an entire space vehicle will be cooled, as in the James Webb Space Telescope. The temperature requirement is measured in degrees Kelvin and the amount of cooling or heat removed is measured in watts/ hour.

Radiators and Insulation
Detector Coolers
Cryo-cooler
Stirling Cryo Cycle
Cryo heat pipe

Instruments Parameters

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INSTRUMENTS

This is a category parameter. Payload or instruments consist of those scientific and/or operational apparatus used to enable the objectives of the mission.

Number of Instruments

Enter the number of instruments in the payload. For this model an instrument is defined a piece of hardware with an independent command and telemetry link into the C&DH subsystem. Like the number of communication bands, the Number of Instruments also is a major cost driver, since it impacts all of the bus' subsystems with the possible exception of propulsion.

Payload Legacy

Select the amount of Payload Legacy. Correctly assessing Payload Legacy is central to an accurate estimate. Virtually all instruments can point to heritage - much of it based on old instruments with little to no applicability to the design and components of instrument under consideration. The key issue is whether instrument heritage is applicable to the planned instrument. If heritage is overly optimistic, then the cost estimate produced will be low. Since Far Out estimates systems will not be built until farther in the future than is usually the case, it is important to consider the state of heritage or legacy that is likely to be in existence when the instrument is actually being designed.

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FAR OUT

ADVANCED SPACE CONCEPTS COST MODEL