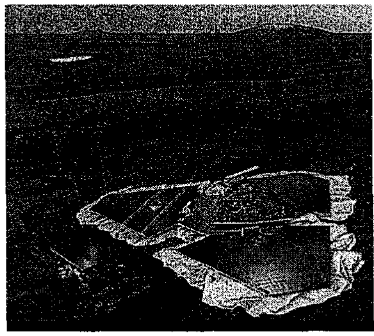
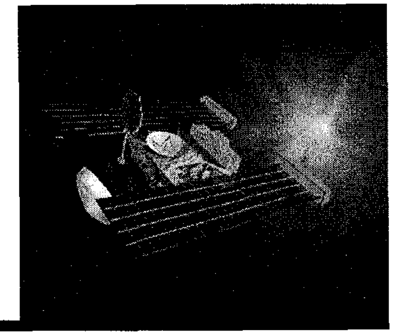


Risk-Adjusted Mission Value



Center for Mission/Technology Analysis and Simulation
and
Center for Space Mission Architecture and Design

Dr. Ralph F. Miles, Jr.
Jet Propulsion Laboratory/ Retired
California Institute of Technology

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Reliability Engineering Program
EER Systems Corporation

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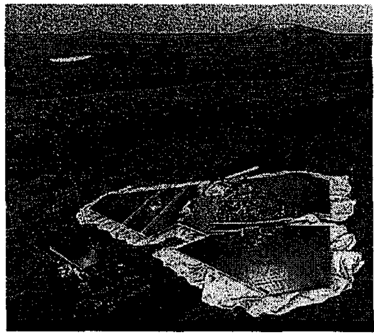
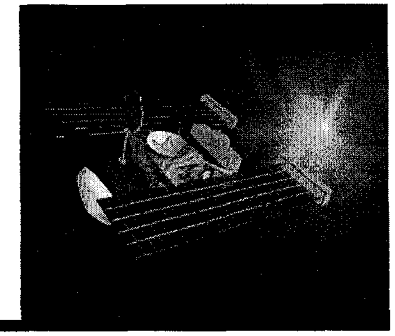
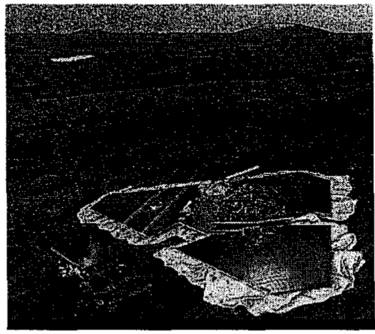


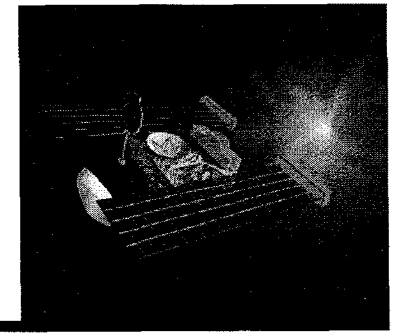
RAMV
A Decision Support System



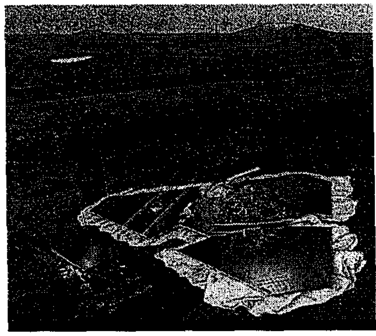
- RAMV = Risk-Adjusted Mission Value.
- RAMV is a Decision Support System.
  - It assembles all the relevant information for decision making.
  - It analyzes and aggregates the information into a form for decision making.
  - In its most formal implementation, it is rigorously consistent with decision theory.
- RAMV is *not* a tool that makes decisions.
  - All decisions are embedded in a larger context than any model can capture.
  - RAMV provides the decision maker with the requisite information and analysis in a useable format.



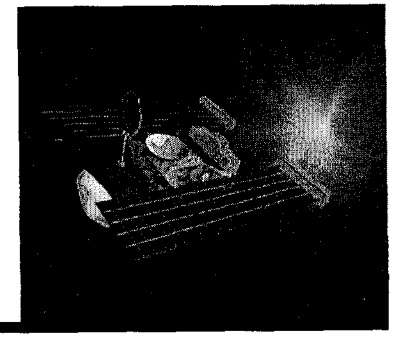
Probabilistic Risk Assessment



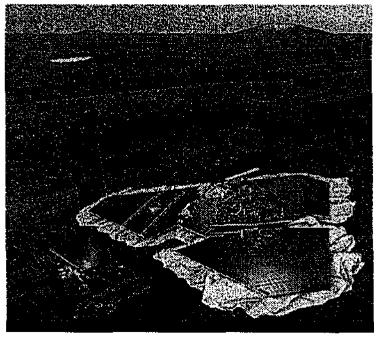
- NASA has requested their Centers to use PRA in the risk management of flight projects.
- PRA uses Event Trees, Fault Tree Analyses, and Failure Mode Effects and Criticality Analyses to determine:
  - The mission failure modes.
  - The chain of events leading to the failure modes.
  - The initiating events for the failure modes.
  - The probabilities that the failure modes will occur.
  - The probability of mission failure.



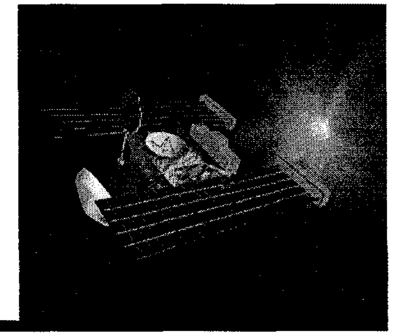
PRA Strengths and Limitations



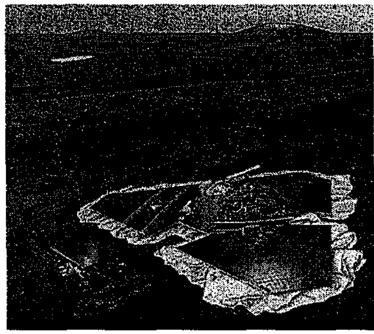
- **PRA** *can* uncover mission failure modes and determine their probabilities of occurrence.
- **PRA** *can* incorporate all types of failure: hardware, software, operations, and environment.
- **PRA** *can* participate in trade-offs between technical risks.
  - E.g., Martian lander weight at surface impact vs. redundancy.
- **PRA** *cannot*:
  - Make trades between mission return and mission risk.
  - Incorporate the risk aversion of the project.
  - Because PRA does not incorporate mission value.



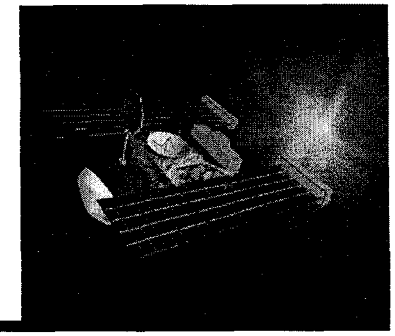
RAMV Contribution



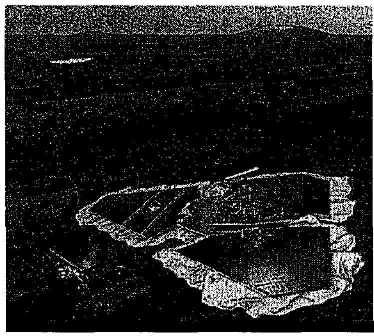
- ❑ **RAMV** *can* make trades between mission return and mission risk.
- ❑ **RAMV** *builds* upon PRA.
- ❑ **RAMV** *does* incorporate mission value.
- ❑ **RAMV** *can* incorporate all the uncertainties in a mission.
    - Mission risk.
    - Mission return.
- ❑ **RAMV** *does* incorporate the risk aversion of the Project Management.
- ❑ **RAMV** *does not* dictate the "best" solution.



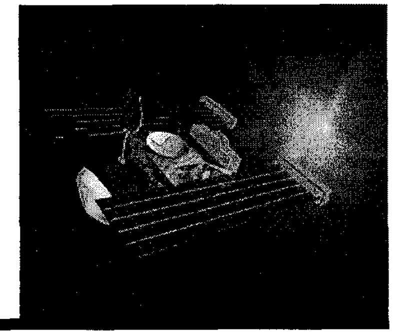
RAMV Overview



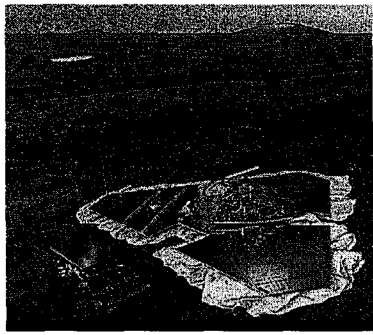
- The RAMV implementation described here considers a mission consisting of a set of risk-free mission outcomes and one failure outcome.
  - RAMV is easily extended to more complex missions.
- The risk-free outcomes *x* ™ *X* are evaluated by the Mission Scientists to obtain *v(x)*.
- The probabilities of success *s(x)* for the mission outcomes are assessed by the Project Engineers.
- The Project Management assigns a risk factor *r*.
  - Based on consideration of a mission failure.
- The following equation rank-orders in preference the risk-free outcomes.
  - $u(x) = s(x)\ [(1-r)v(x) + r]$



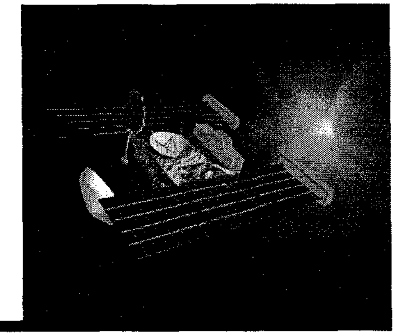
Acceptable Outcomes



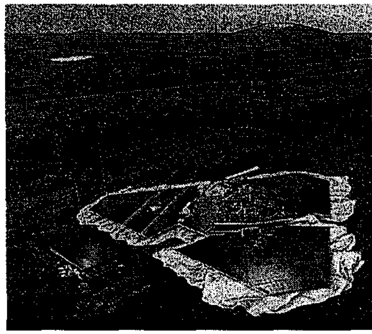
- ❑ The Project Scientists and the Project Management first must reach agreement on a set of acceptable risk-free (no failure) outcomes.
  - This has to be done independent of the methodology to be employed for selecting the preferred mission.
- ❑ The outcomes must be sufficiently well defined such that:
  - The Project Scientists can assign science values to the outcomes.
  - The Project Engineers can calculate probabilities of success.
  - The Project Management can specify a level of risk-aversion.



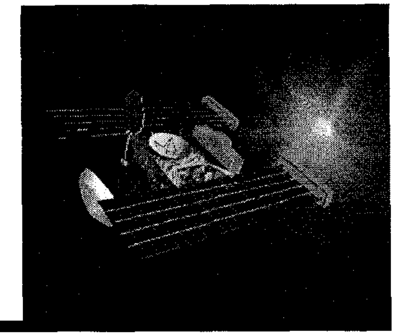
Sources of Information



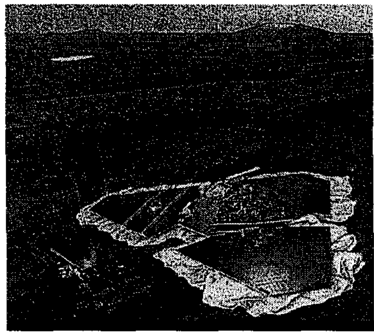
- Three sources of information enter into determining risk-adjusted mission values for alternatives.
  - Project Scientists assign science values *v(x)* to risk-free outcomes because they have the scientific knowledge.
  - Project Engineers assess probabilities of success *s(x)* for outcomes because they have the technical knowledge for probabilistic risk assessment.
  - Project Management assigns the risk aversion level *r* because they are responsible for managing risk.



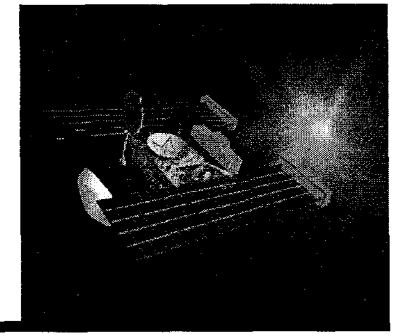
RAMV Methodology: Science



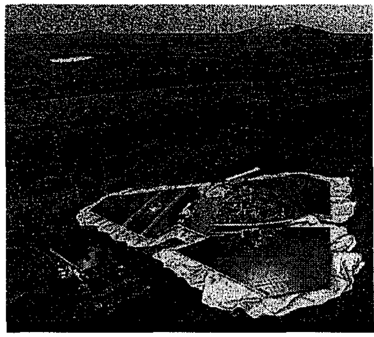
- Project Scientists assign science values *v(x)* to risk-free (no failure) outcomes based on whatever method they prefer. The science values are then rescaled to range from 0.0 to 1.0.
  - To be rigorously consistent with decision theory, the scientists would need to assign a science value *v(x)* to each risk-free outcome *x* based on indifference between outcome *x* for sure and a gamble that gives probability *v(x)* to the most-preferred risk-free outcome and probability *1 – v(x)* to the least-preferred risk-free outcome.



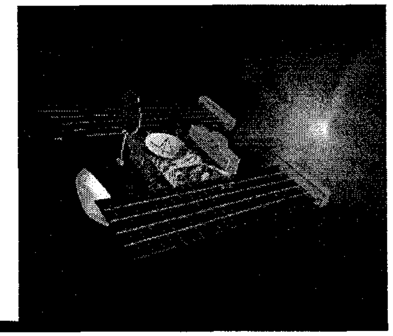
RAMV Methodology: PRA



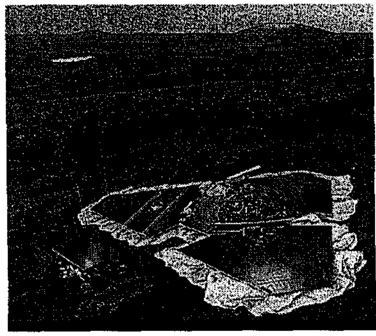
- Project Engineers use probabilistic risk assessment to assess the probabilities of success *s(x)* for outcomes.
  - The probabilities of success *s(x)* are derived from compounding probabilities over the nodes event trees.
  - The probabilities associated with the nodes of event trees are derived from fault trees and failure modes and effects analyses.
- Where there are uncertainties in the probabilities, the *s(x)* are constructed from Monte Carlo simulations over all relevant phases of the mission.



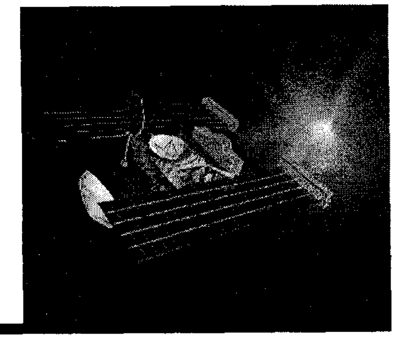
Management Outcome Values



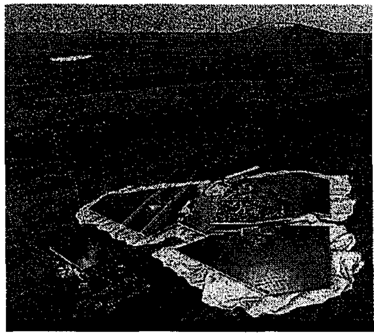
- The Project Management could assign a "fractional" value *f* to the fraction of mission value achieved by the least-preferred mission outcome $\mathbf{x_0}$ compared to the most-preferred mission outcome $\mathbf{x^*}$.
  - $\mathbf{m(x_0) = \mathit{f}\, m(x^*)}$.
    - "*f*" is a measure of Mission $\mathbf{x_0}$ value relative to Mission x*.
    - "f" could be the fraction of mission objectives achieved.
  - But most Project Managements would not take a (1 - *f*) chance of failure to obtain $\mathbf{x^*}$ if the project could obtain $\mathbf{x_0}$ for sure. It would require that the project not be risk-averse with respect to failure.
- *f* needs to be "Risk-Adjusted" to incorporate the risk aversion of the Project Management.
  - Thus the name "Risk-Adjusted Mission Value."



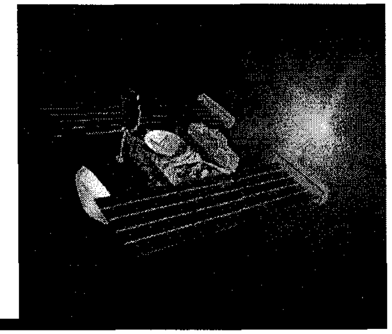
Expected Utility Theory



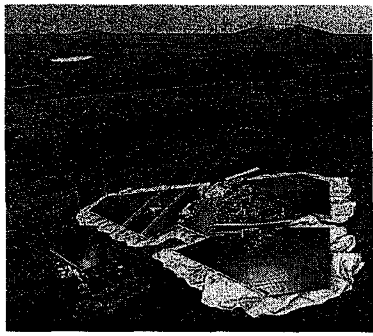
- Decision Theory includes the theory of individual decision-making.
  - This is called expected utility theory.
  - The word "utility" is used rather than "value."
    - It was discovered as early as 1713 that decisions could not be based on "expected value" due to risk-aversion.
    - The first axioms for expected utility theory were developed by von Neumann and Morgenstern in 1944.
  - Expected utility theory and its practical counterpart, decision analysis, are taught in every major university.
  - Expected utility theory is an axiomatic normative theory for individual decision-making.
    - If you accept the axioms, then the decision rule follows.



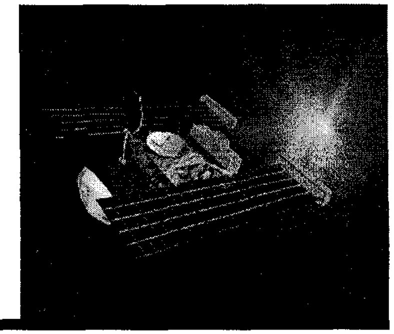
Axioms of Expected Utility Theory



- Axioms:
  - Ordering of outcomes.
    - Asymmetry, completeness, and transitivity.
  - Reduction of compound gambles.
    - Gambles over gambles can be considered.
  - Continuity.
    - There is a gamble equivalent to any outcome.
  - Substitutibility.
    - A gamble can be substituted for any outcome.
  - Monotonicity.
    - Preferred gambles have higher probabilities of success.

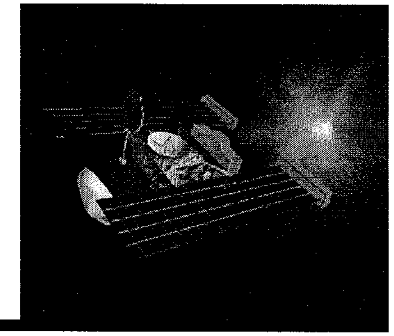


Theorem of Expected Utility Theory

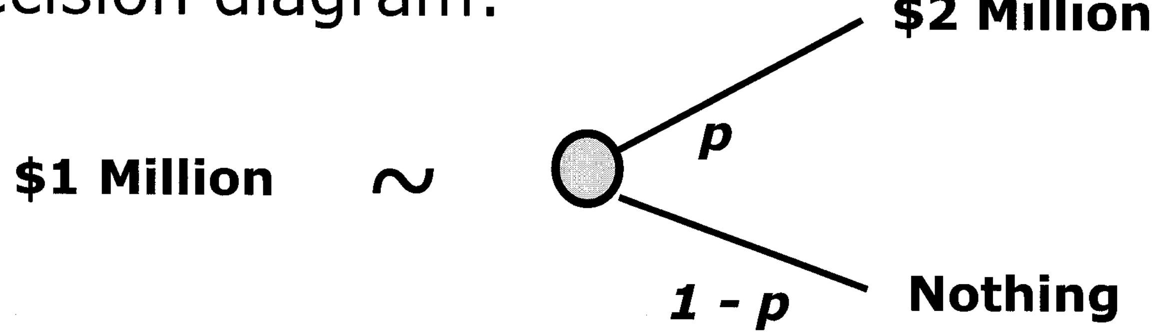


- There is a straightforward method for assigning utilities to outcomes.
- Given the axioms, numbers called utilities can be assigned to the outcomes of a gamble such that the utility of the gamble is the expected value of the utilities of the outcomes of the gamble.
- The utility numbers assigned are unique up to a positive affine transformation.
  - u′ = ♋ u(x) + ♌ where ♋ > 0.
- The gamble with the highest utility is the preferred gamble.

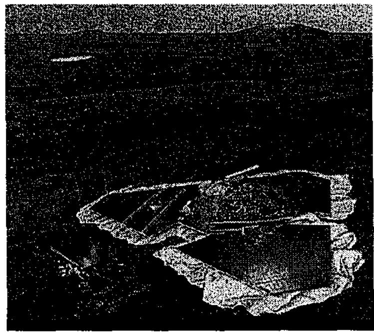
Incorporating Risk Aversion in Decisions



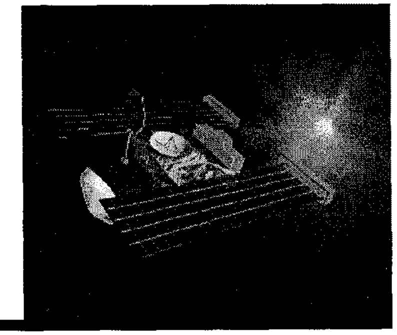
- Would a manager prefer $1 Million or a 50/50 chance at $2 Million or nothing?
  - The expected value is $1 Million.
  - Most managers would take the $1 Million.
- What probability *p* would most managers require to be indifferent between these rewards?
- A decision diagram:



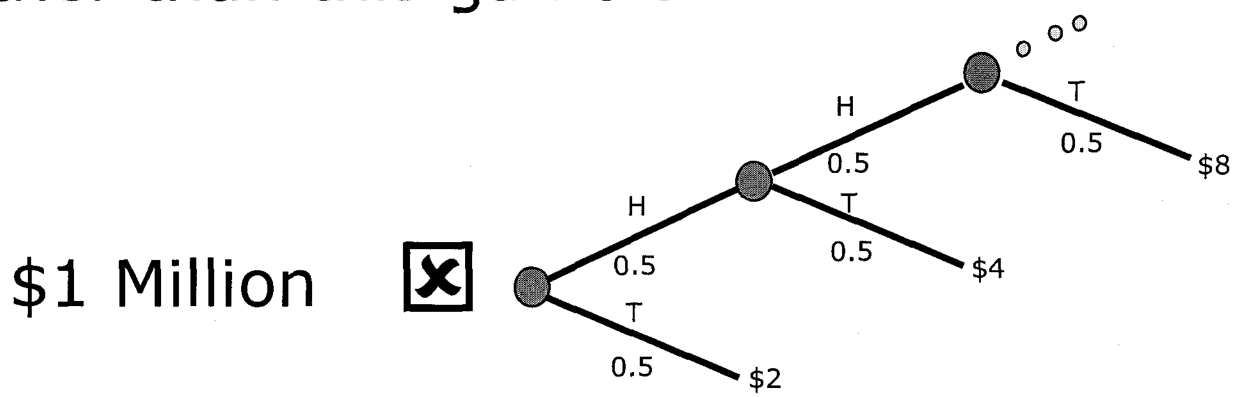
- The difference between *p* and 0.5 is a measure of risk aversion.



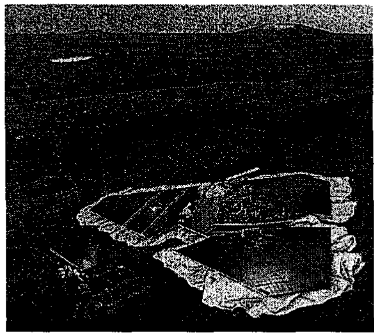
All Managers Are Risk-Averse



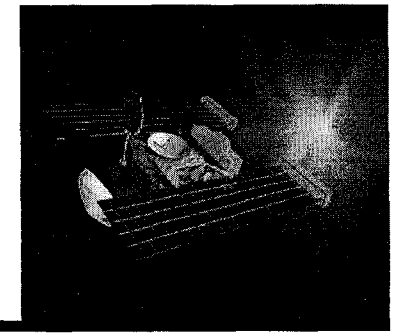
- If the stakes are high enough, all managers are risk averse.
- All managers would take take the $1 million rather than this gamble.

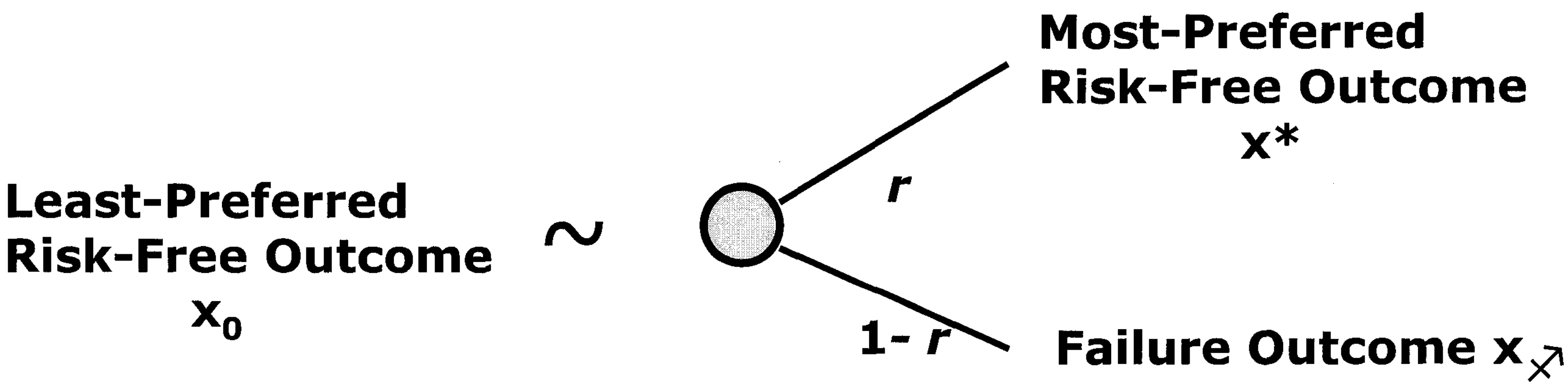


- But the expected value of this gamble is ◎ !
  - Expected value =1 + 1 + 1 + . . .



Incorporating Risk Aversion in the Project

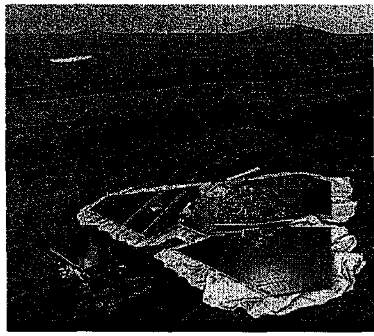




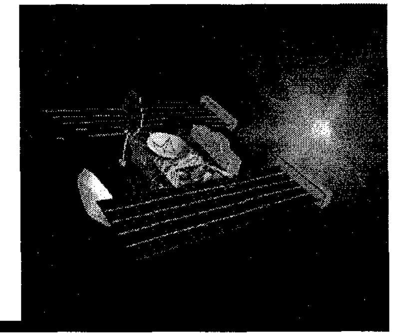
- The Project Management selects "*r*" such that he is indifferent between:

- Receiving the Least-Preferred Risk-Free Outcome x_0 for sure, OR
- Receiving the Most-Preferred Outcome x^* with probability "*r*" and the Failure Outcome $x_{♐}$ with probability "1 – *r*".

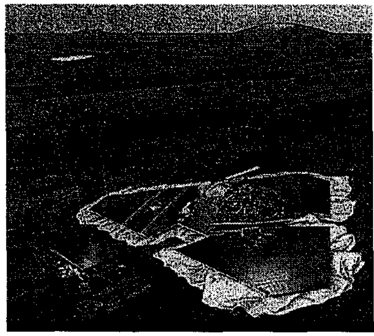
- The difference between "*r*" and "*f*" is a measure of the risk aversion of the Project Management.



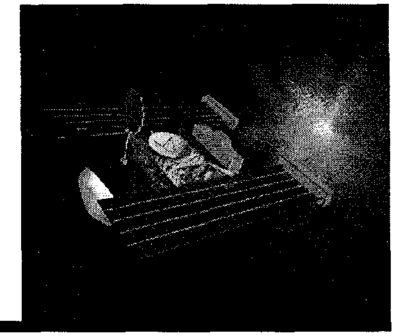
RAMV Equation with Risk Aversion



- Risk-adjusted mission value $u(x)$:
  - $u(x) = s(x)\,[(1-r)\,v(x) + r\,]$.
- For risk factor $r = 0$, $s(x)\,v(x)$ is the risk-adjusted mission value.
  - The risk-adjusted mission value is the expected value as calculated from the science value.
- For risk factor $r = 1$, $s(x)$ is the risk-adjusted mission value.
  - The risk-adjusted mission value is just the probability of success, and is not influenced by the science value.
- The Project Management does not have to reveal their value of r, only the selected alternative.

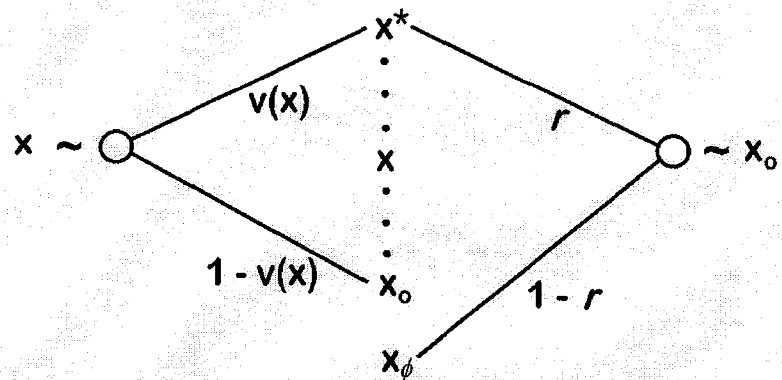


RAMV Flowchart



(1) Project Management and Scientists select Mission set $x \in X$.

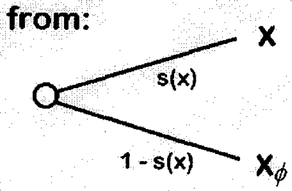
(2) Scientists assess $v(x)$.



(3) Engineers assess $s(x)$. →

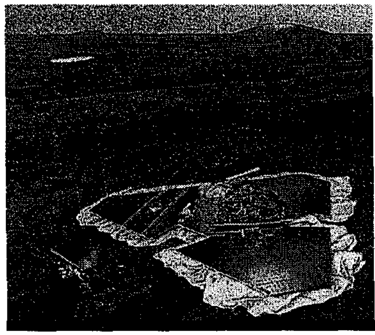
(4) Project Management assesses r to obtain $u(x) = [(1 - r)v(x) + r]$.

(5) EU(x) determined from:

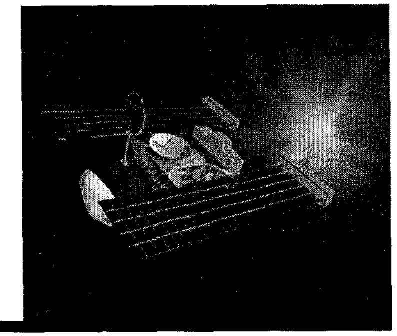


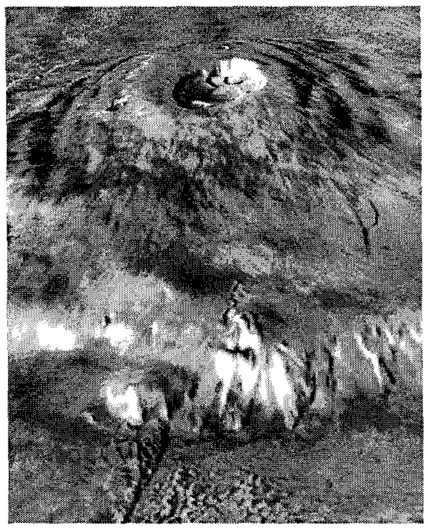
← (6) $RAMV(x) = EU(x) = s(x)\,u(x)$.

$RAMV(x) = s(x)[(1 - r)\,v(x) + r]$.



Example #1: Mars Landing Site



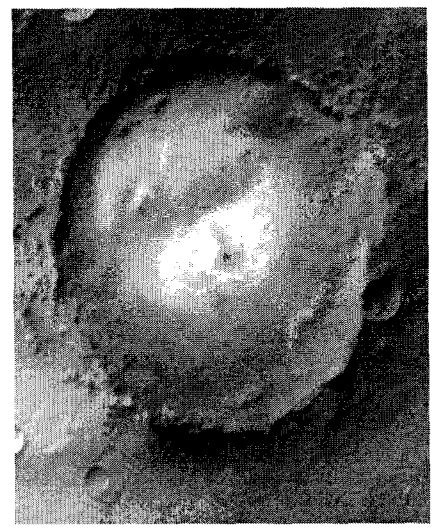


Site 1:

Olympus Mons

Site 2:

Candor Chasm

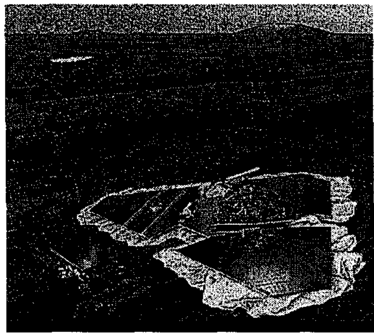


Site 3:

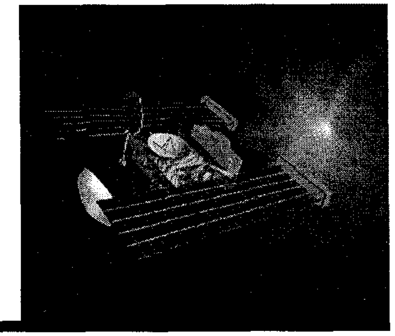
Unnamed Crater

Site 1:

Dao Vallis



Monte Carlo Simulations



- The PRA probabilities are constructed from Monte Carlo simulations for surviving landing.
- The simulations incorporate:
  - Simulation of navigation errors on landing dispersion.
  - Simulation of atmospheric effects on landing dispersion.
  - Simulation of the Martian terrain at landing site.
  - Variation in the terminal velocity of the lander.
  - Wind conditions at the surface, and
  - Robustness of the lander with respect to surface impact.

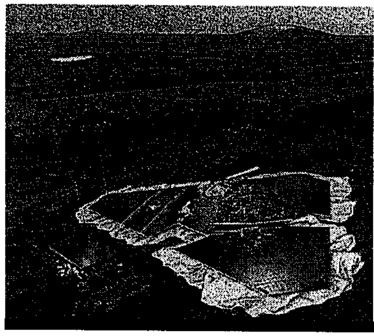
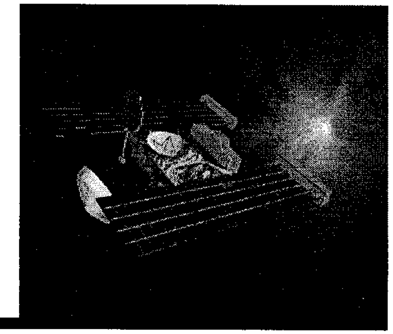
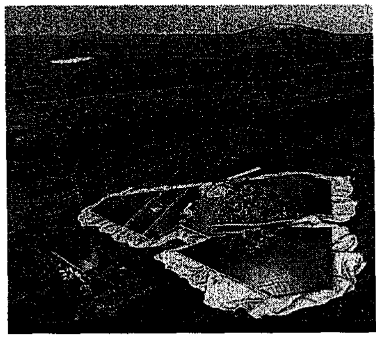


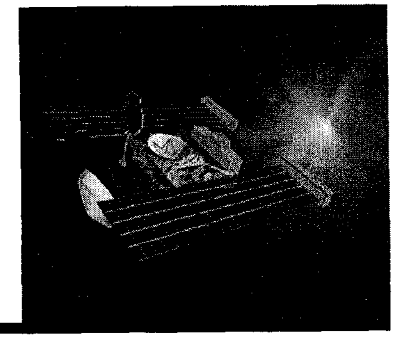
Table for Risk-Free Outcome Utilities



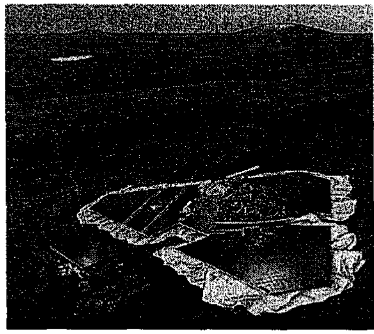
Landing Site	Success Probability	Risk-Free Outcome Utility
Site 1 Olympus Mons	0.60	1.00
Site 2 Candor Chasm	0.75	0.70
Site 3 Unnamed Crater	0.85	0.40
Site 4 Dao Vallis	0.91	0.00



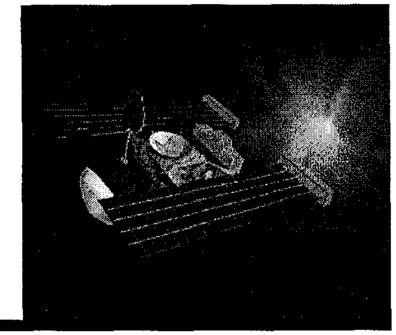
Expected Risk-Free Outcome Utilities



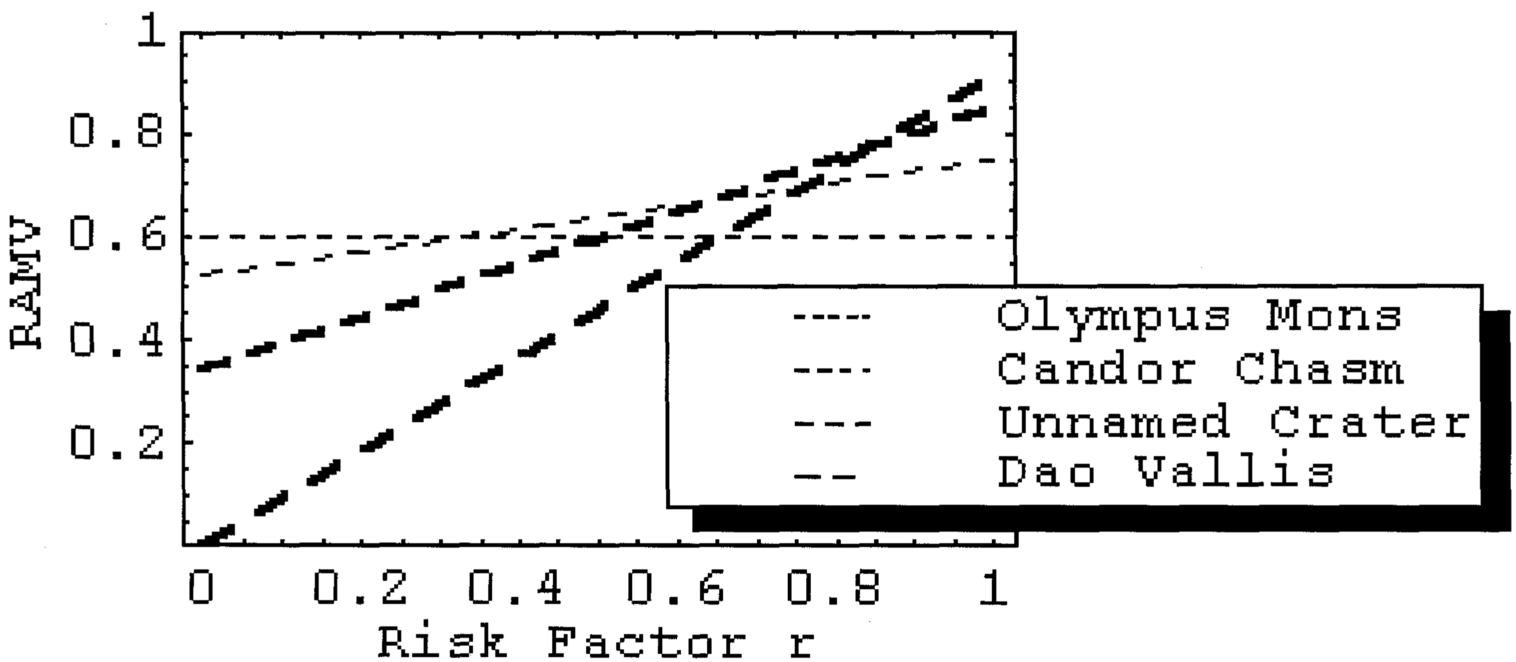
Martian Landing Site	Expected Utility
Site 1 Olympus Mons	0.60
Site 2 Candor Chasm	0.53
Site 3 Unnamed Crater	0.34
Site 4 Dao Vallis	0.00

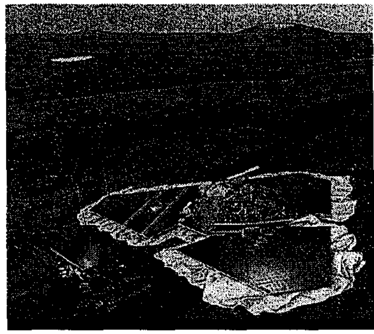


RAMV vs. Risk Factor

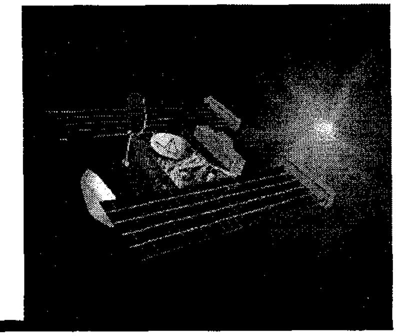


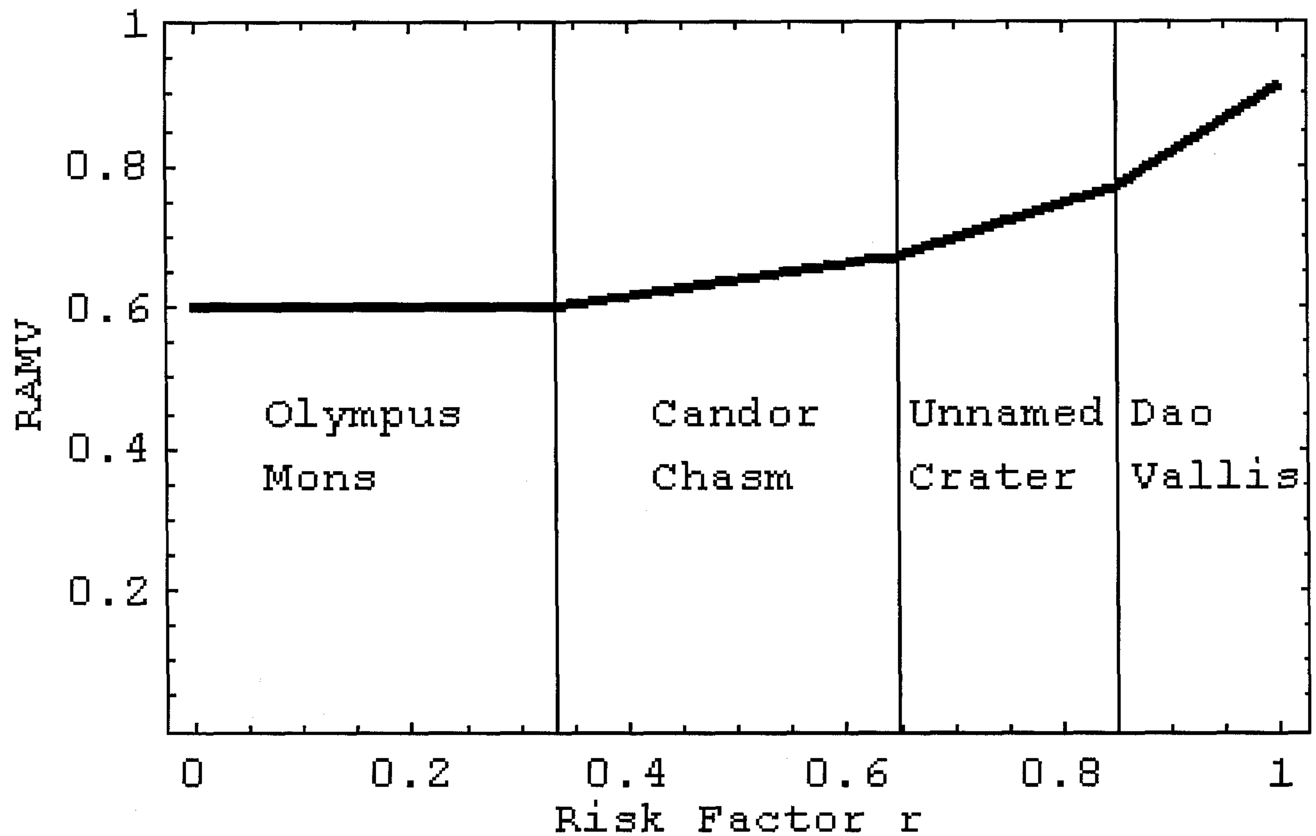
$$RAMV(x) = u(x) = s(x)\,[(1-r)\,v(x) + r\,]$$

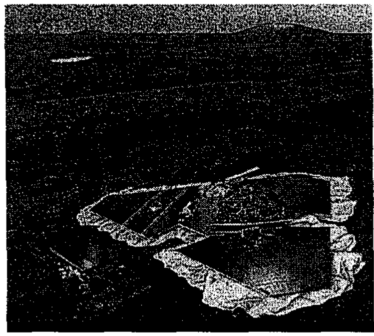




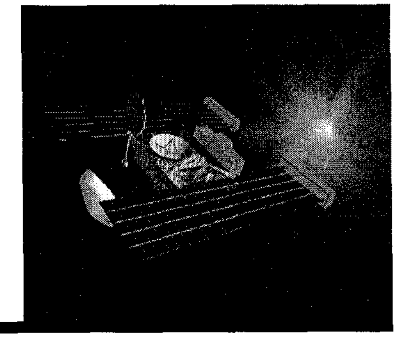
Optimum Site vs. Risk Factor *r*



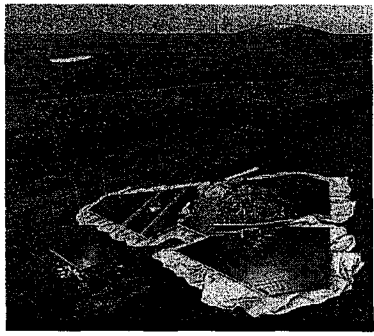




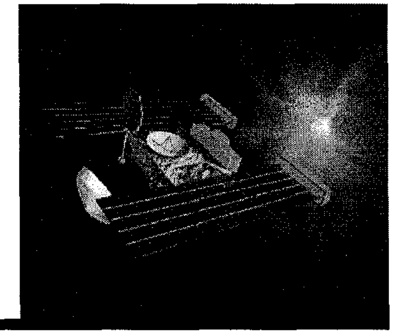
Example #2: RAMV for Mars EDL

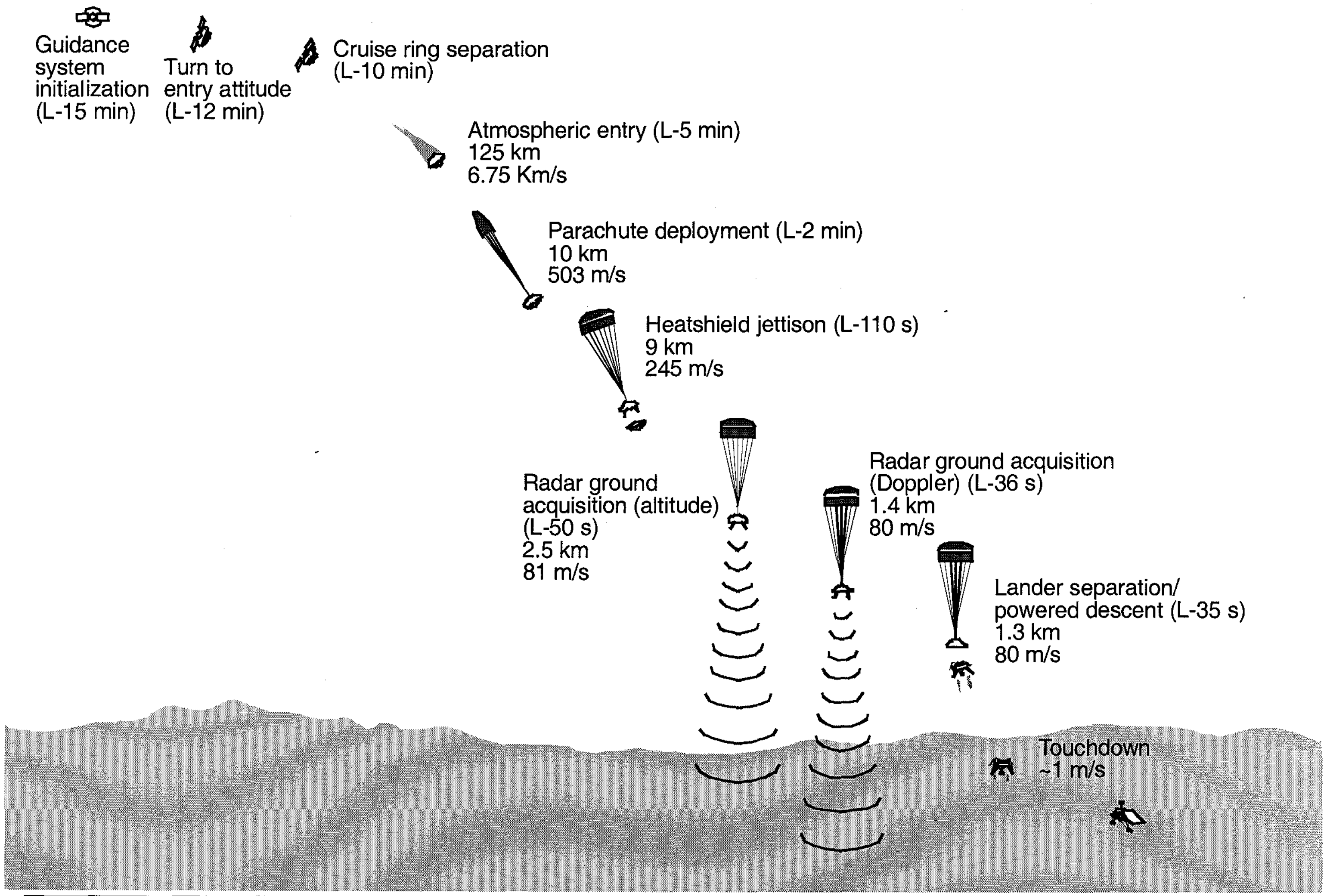


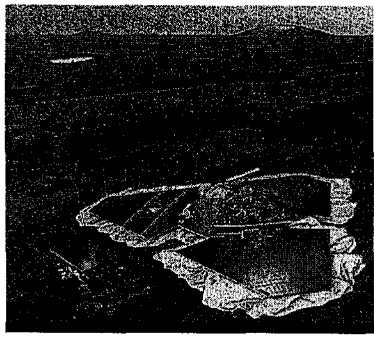
- ❑ RAMV for Mars Entry, Descent and Landing.
- ❑ Two options.
  - Basic Design: System A.
  - System B adds one additional science instrument.
- ❑ The probabilities and outcome utilities will change.
  - The probabilities of success for System B decrease.
  - The risk-free science values for System B increase.
- ❑ Which System is preferred?
  - Answer can depend on the option and the landing site.



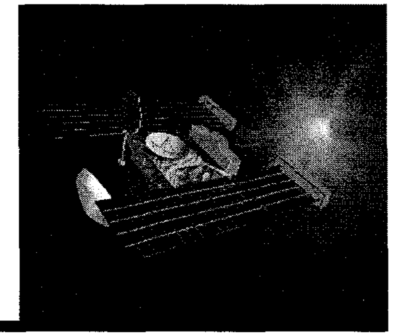
Mars Entry, Descent and Landing

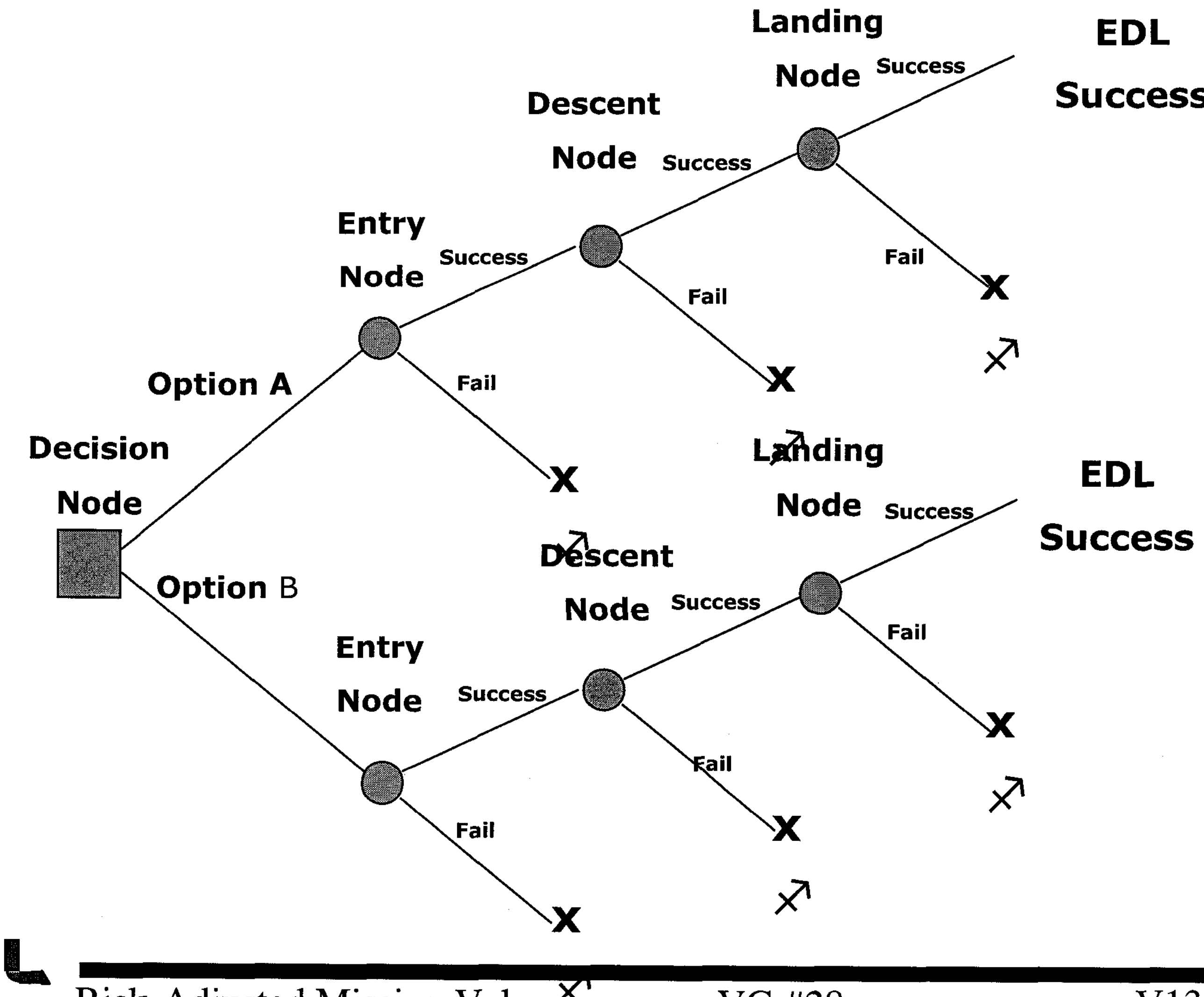


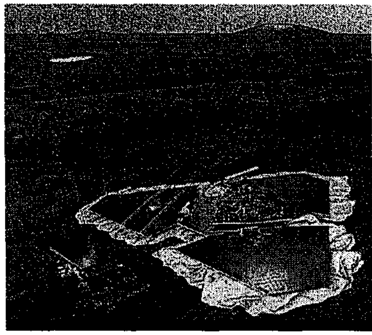




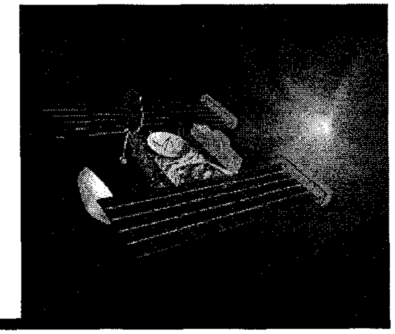
Decision Tree for Mars EDL



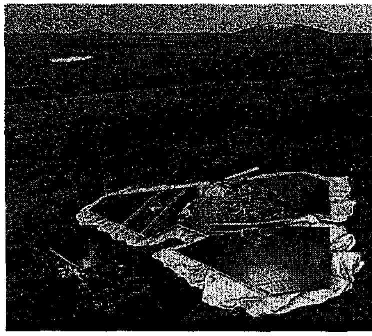




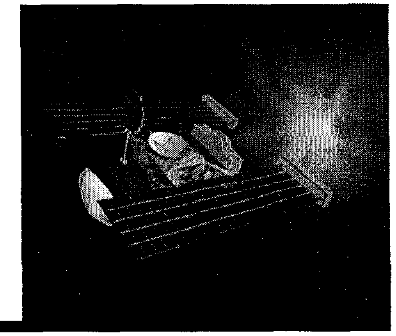
Probabilities and Risk-Free Mission Utilities



	P(E)	P(D)	P(L)	U(EDL)
Option A				
Site 1	0.99	0.96	0.6	0.75
Site 2	0.99	0.96	0.75	0.53
Site 3	0.99	0.96	0.85	0.30
Site 4	0.99	0.96	0.91	0.00
Option B				
Site 1	0.98	0.92	0.4	1.00
Site 2	0.98	0.92	0.6	0.80
Site 3	0.98	0.92	0.75	0.60
Site 4	0.98	0.92	0.89	0.30

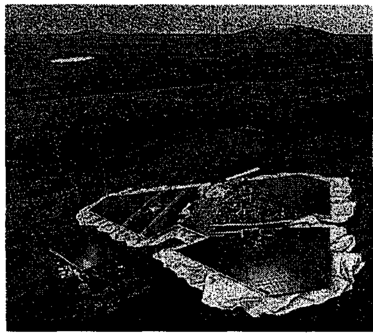


Optimum Site Depends on Option <u>and</u> *r*

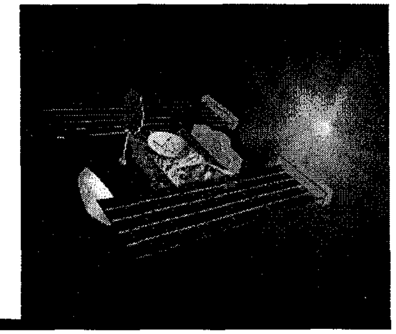


Risk-Adjusted Mission Values

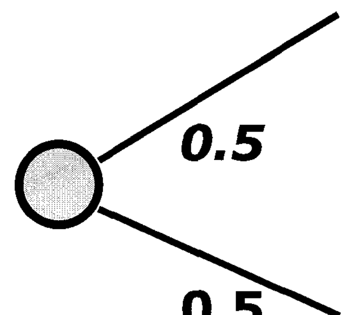
	r	*r*	*r*	*r*	*r*
	0.000	0.250	0.500	0.750	1.000
Option A					
Site 1	0.428	0.463	0.499	0.535	0.570
Site 2	0.378	0.462	0.546	0.629	0.713
Site 3	0.242	0.384	0.525	[illegible]	0.808
Site 4	0.000	0.216	0.432	0.649	[illegible]
Option B					
Site 1	0.361	0.361	0.361	0.361	0.361
Site 2	0.433	0.460	0.487	0.514	0.541
Site 3	0.406	[illegible]	0.541	0.609	0.676
Site 4	0.241	0.381	0.522	0.662	0.802



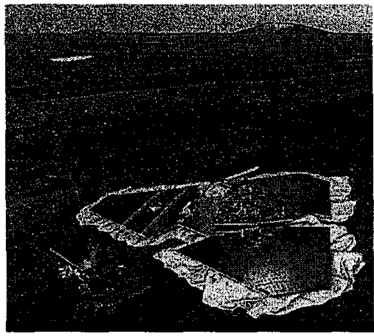
Example #3: Comet Flyby



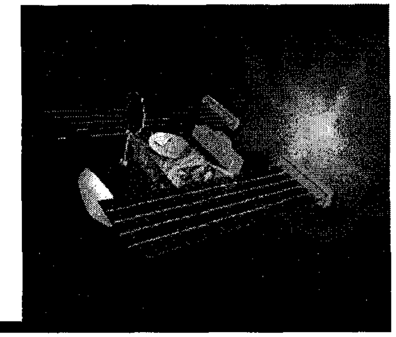
- Assume flyby altitudes between 100 km and 1,000 km of the nucleus are acceptable to both Project Management and Project Scientists.
- Assume scientists' utility function:
  - $u(x_{1,000}) = 0.0 \quad u(x_{100}) = 1.0$



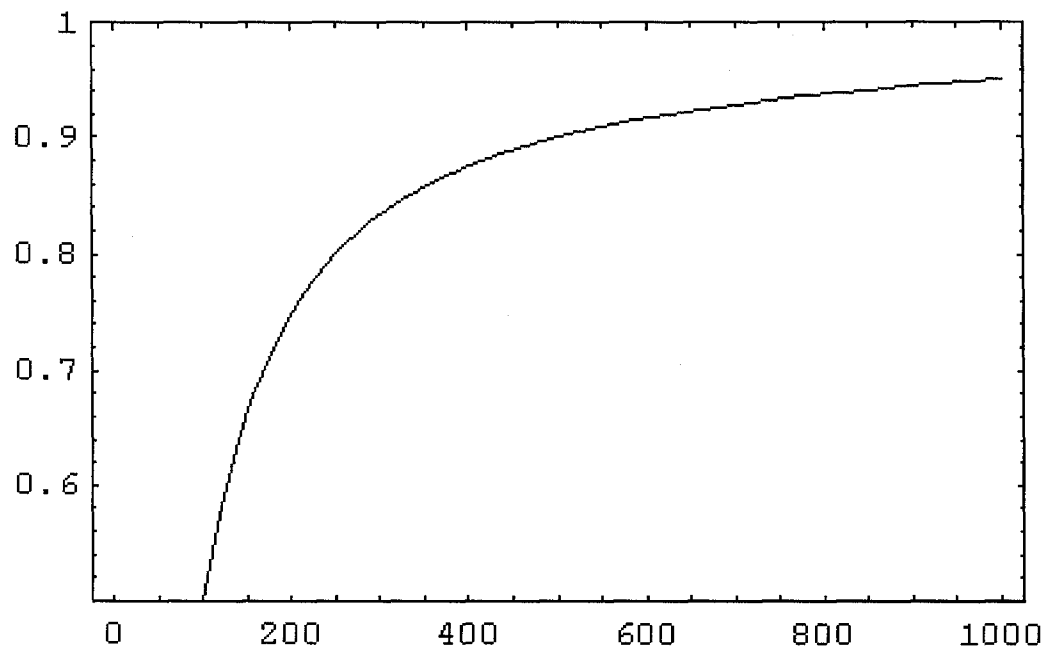
- Assume u(750) = 0.5, as shown above.
- Then, assuming constant risk aversion:
  - $u(x) = 1.14 - 0.115\, e^{0.00230\,x}$



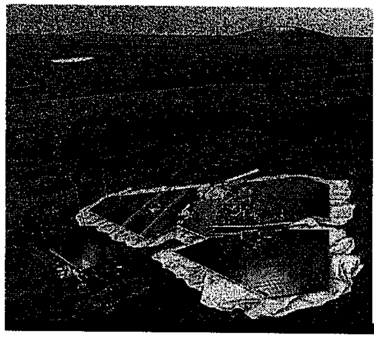
PRA for Comet



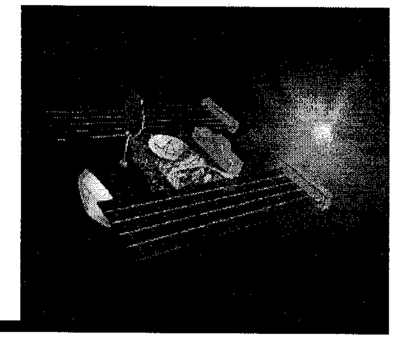
- Assume risk increases as (a + b/*d*), where *d* is the flyby closest-approach distance.



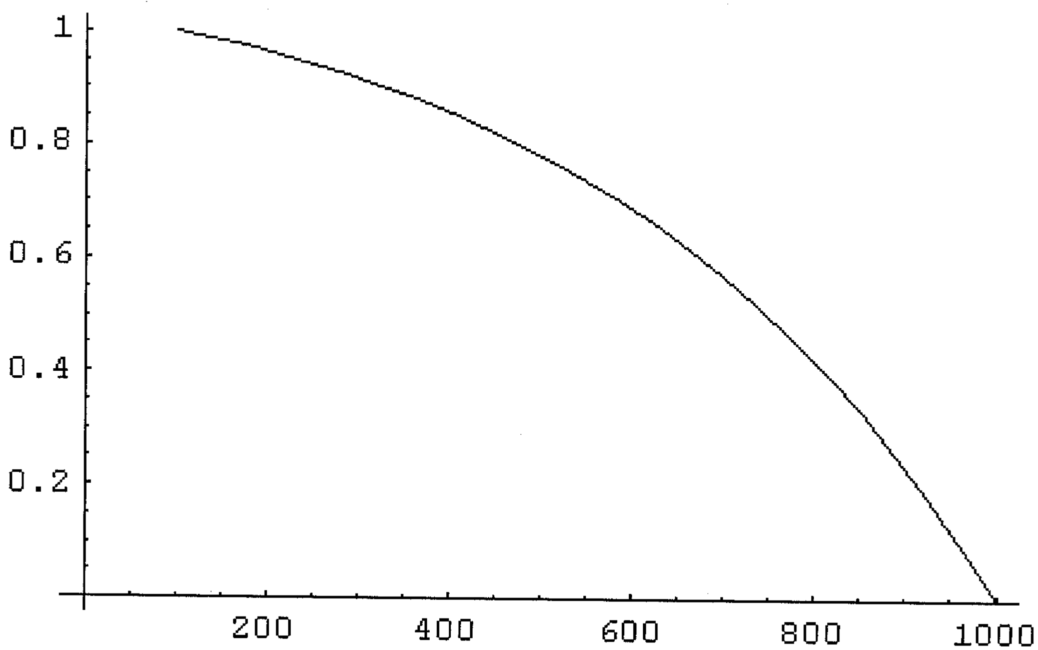
- Assume s(x) = 0.5 @ 100 km and 0.95 @ 1,000 km.

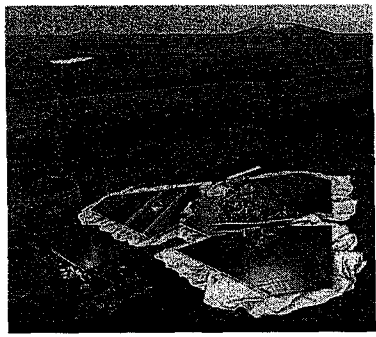


Science for Comet

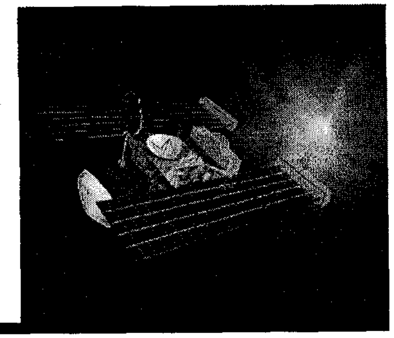


- Assume indifference between science at 750 km and a 50/50 gamble between 100 km and 1,000 km. This yields the curve for *s(x)*.

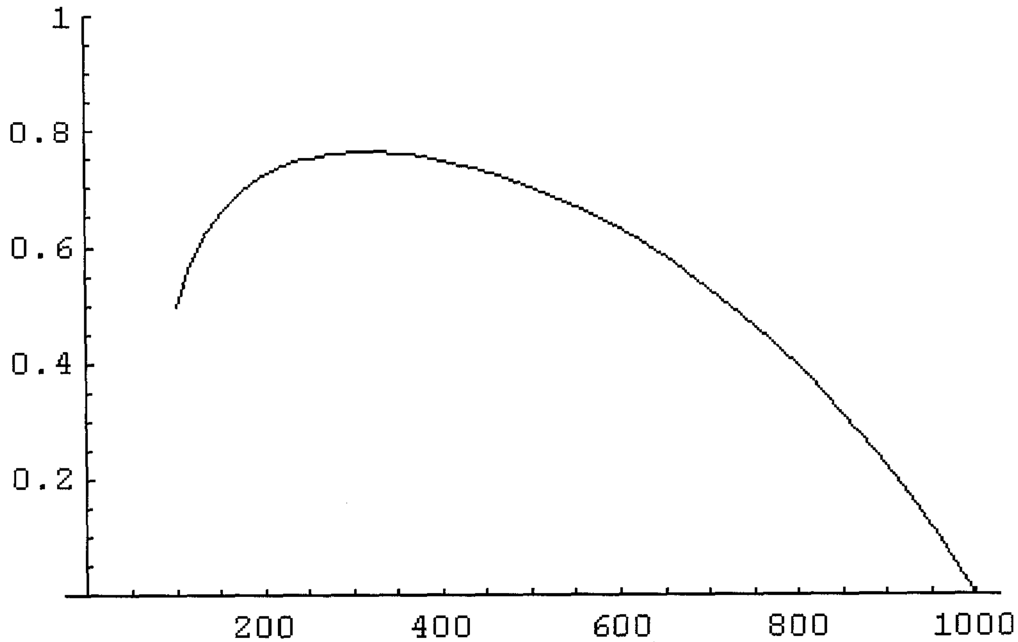




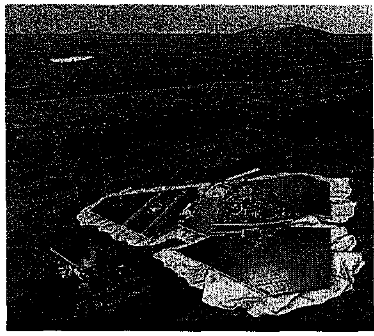
Expected Utility for Comet Science



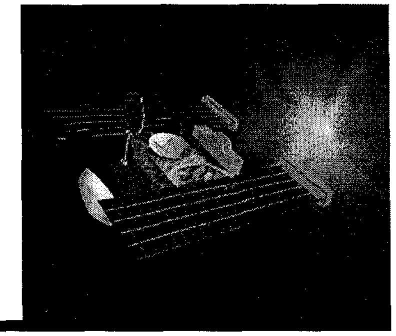
- ❑ Expected Utility= *s(x) v(x)* for Comet Science.



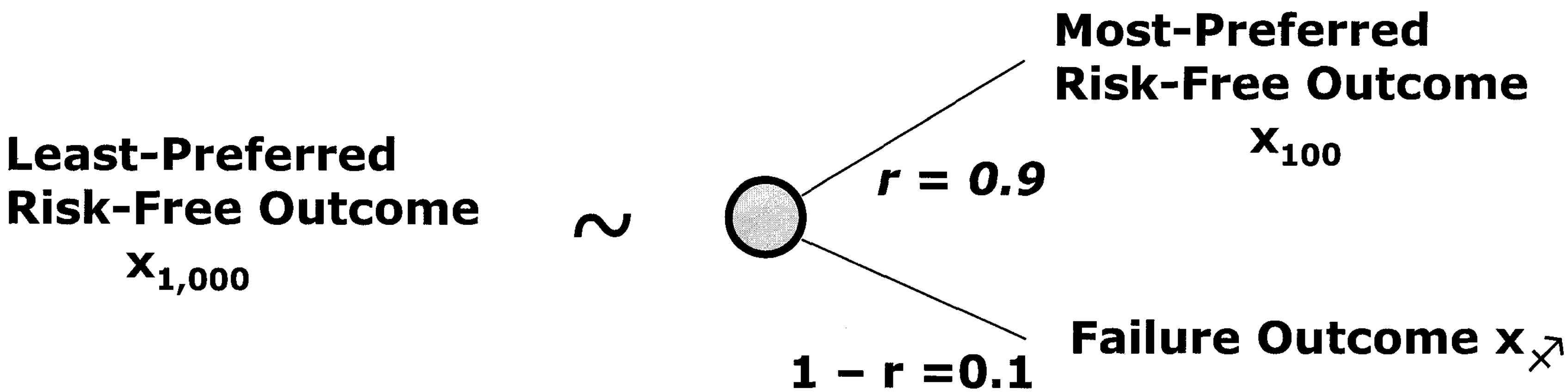
- ❑ The maximum Expected Utility is at 315 km.



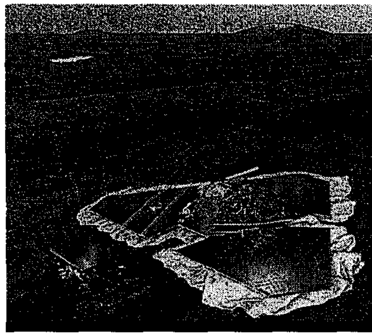
Risk Factor *r* for Comet Flyby



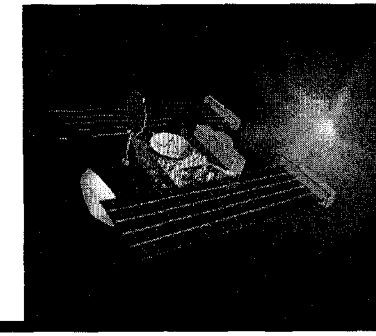
- ❑ Assume that the Project Management is indifferent between a flyby at 1,000 km and a gamble that yields a flyby at 100 km with probability *r* = 0.9 and a failure with probability = 0.1.

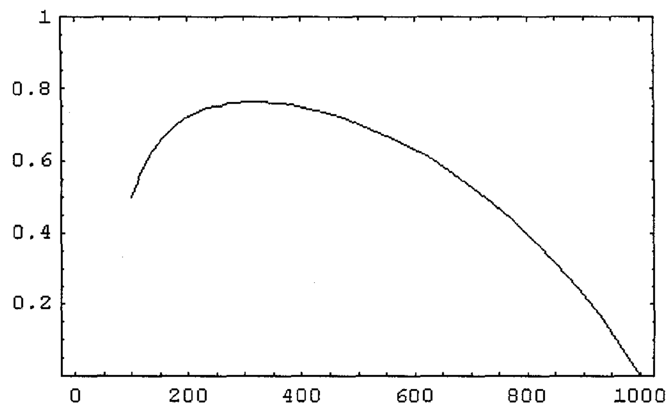


- ❑ Risk Factor: *r* = 0.9
- ❑ (1 – *r*) = 0.1 is not the probability of mission failure.

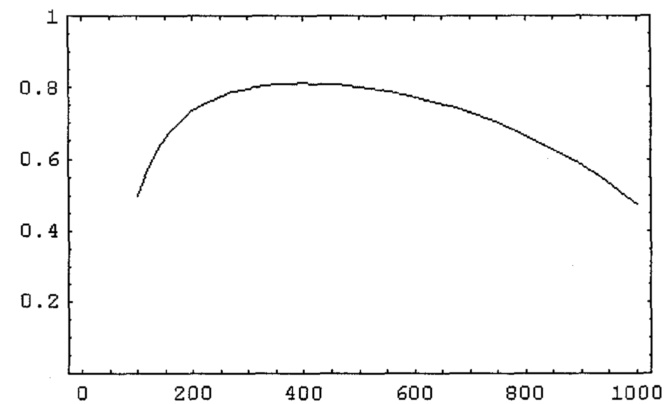


Different RAMV *r* Curves for Comet

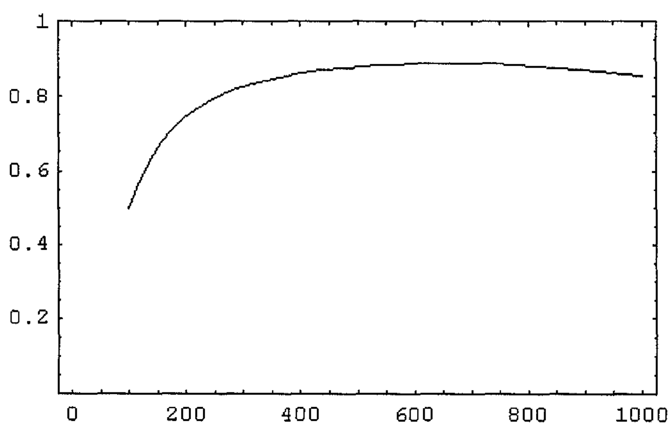




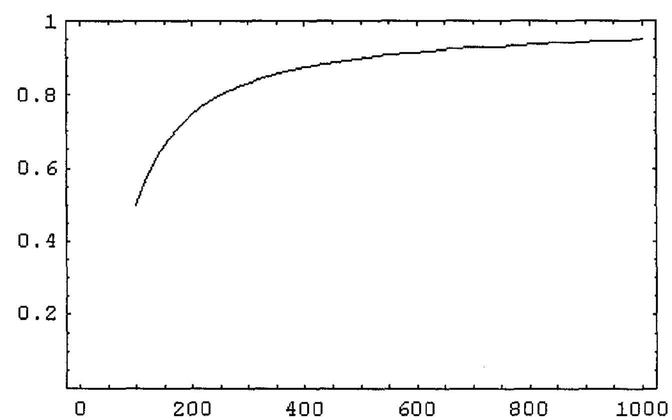
For *r* = 0.0, RAMV Max @ 315 km. Risk = 0.16.



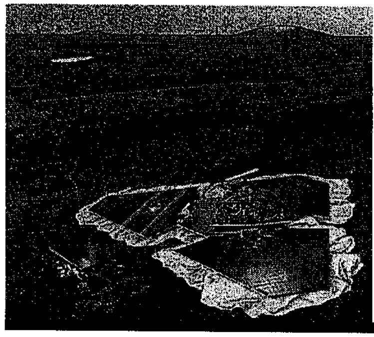
For *r* = 0.5, RAMV Max @ 400 km. Risk = 0.13



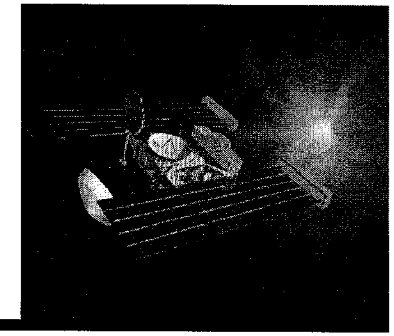
For *r* = 0.9, RAMV Max @ 658 km. Risk = 0.08.



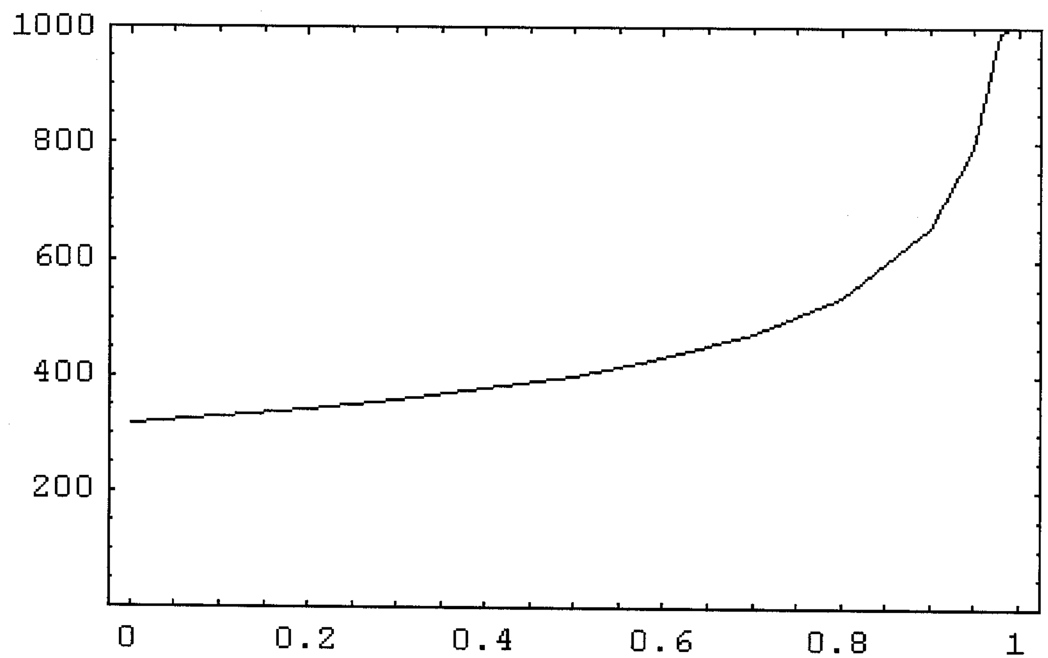
For *r* = 1.0, RAMV Max @ 1,000 km. Risk = 0.05.



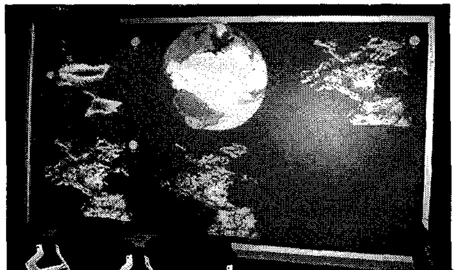
Optimum Flyby Altitude vs. Risk Factor *r*



- ❑ As the Risk Factor *r* varies from 0 to 1, the optimum flyby altitude varies from 315 km to 1,000 km.



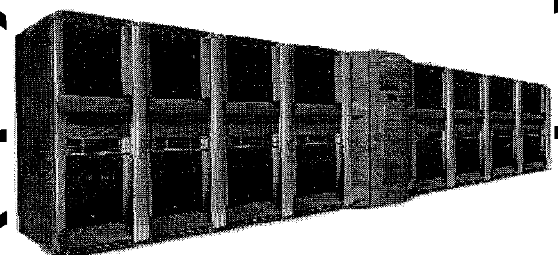
High Performance Computing and Communications JPL Assets



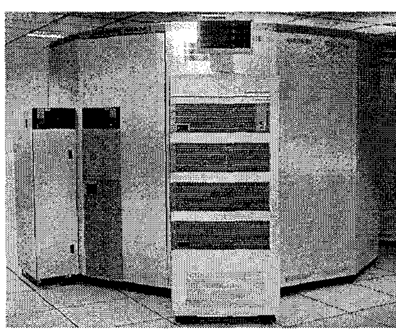
PowerWall
- •6 Electrohome DLV 1280
- •1 Digital Projection 6SX
- •7.8 MegaPixel Display

SGI SV1-A
- •16 CPU Parallel vector Processor
- •1000 MFLOPs/cpu
- •8 Gigabyte Memory
- •480 Gigabyte Disk

To NTON

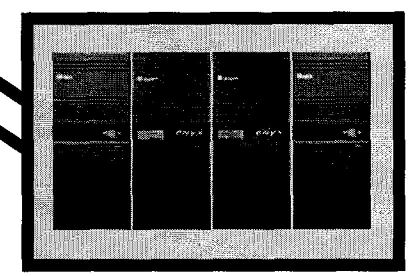


To JPL Auditorium

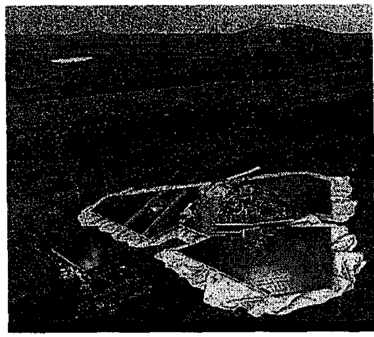


SGI Origin 2000 Reality Monster
- •128 CPU Parallel Processor
- •600 MFLOPs/cpu
- •32 Gigabyte main memory
- •2.2 Terabyte Disk

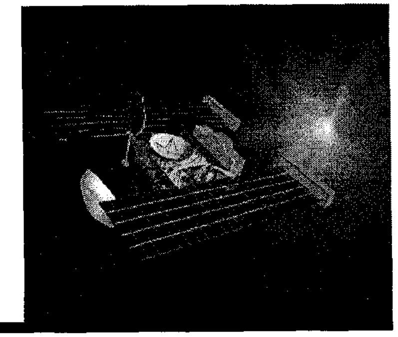
Storage Tek Silo
- 6000 tape capacity
- 50 Gigabytes per tape
- 1000 tapes currently in silo
- Maximum capacity:300 Terabytes



SGI Dual Power Onyx
- •12 CPU processor
- •500 MFLOPs/cpu
- •4Gigabyte main memory
- •512 Gigabyte Disk



RAMV Summary



- RAMV is a Decision Support System.
- RAMV is applicable where different constituencies participate in the mission selection process.
  - Scientists.
  - Engineers
  - Project Management.
- RAMV analyzes and aggregates the information for decision making by the Project Management.
- The RAMV process is transparent to all interested parties.