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SPACE ADVANCED RESEARCH TEAM

New Trends in Astrodynamics and Applications VI

ROBUST DESIGN OF DEFLECTION ACTIONS FOR NON-COOPERATIVE TARGETS

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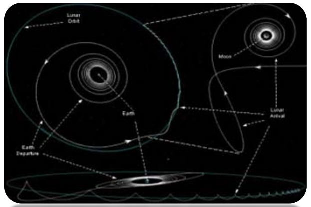
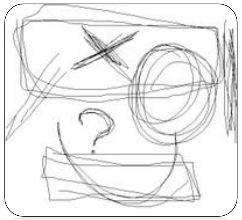
Agenda

Problem Definition



Low-thrust Analytical Integration

Deflection and System Models



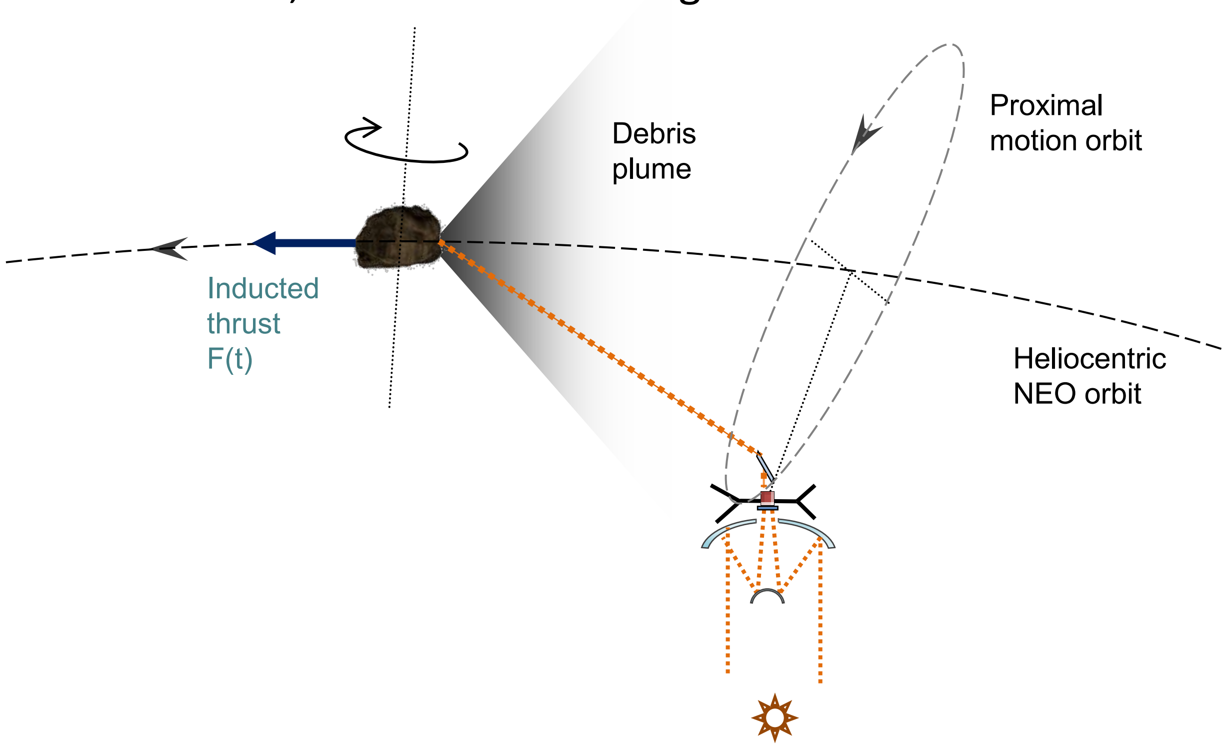
Evidence-based Robust Design

Results and Conclusions

Problem Definition

Robust Design of Deflection Actions for Non-Cooperative Targets

- The Solar Laser Ablation concept envisages the use of a Space-based solar pumped laser system to sublimate the surface material of the target object.
- Sublimation creates a low thrust acceleration which, over an extended period of time, will deviate the target's orbit.

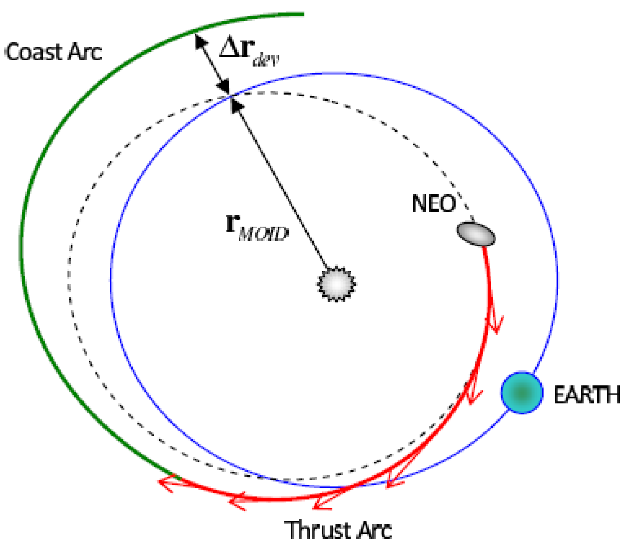


Maximum Impact Parameter Problem

- Given a **spacecraft mass $m_{s/c}$** producing a deviation action **a_d** for a **time $\Delta t = t_e - t_i$** **maximise the impact parameter** on the b-plane at the expected time of the impact.

- In the Hill reference frame, this is computed as:

$$\Delta\mathbf{r}_{dev}\,\Psi = \mathbf{k}\, r_{A_{dev}}\;\mathbf{k}\left(\;_{A_{dev}},\;\;_{A_0}\right) - \begin{bmatrix} r_{A_0} \\ 0 \\ 0 \end{bmatrix}$$



- With $\mathbf{k}_{A_0}$ and $\mathbf{k}_{A_{dev}}$ as the Keplerian elements of the nominal and deflected asteroid orbits.

- **To compute $\mathbf{k}_{A_{dev}}$ one can integrate the Gauss' Variational equations with the ablation induced thrust acceleration.**

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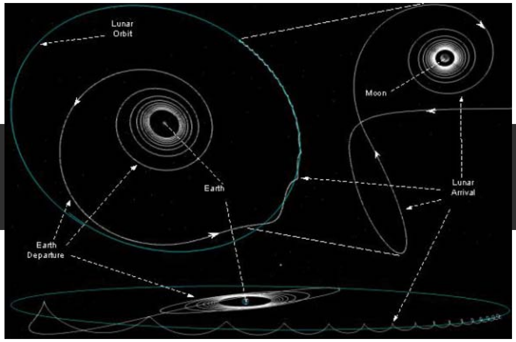
Low-Thrust Analytical Integration



Equations of Motion

- Non-singular Equinoctial elements:
  - No singularities for zero-inclination and zero-eccentricity orbits.

$$\mathbf{X}=\begin{Bmatrix} a \\ P_1 = e\cdot\sin(\Omega+\omega) \\ P_2 = e\cdot\cos(\Omega+\omega) \\ Q_1=\tan\dfrac{i}{2}\sin\Omega \\ Q_2=\tan\dfrac{i}{2}\cos\Omega \\ L=(\Omega+\omega)+\vartheta \end{Bmatrix}$$

- Gauss planetary equations in Equinoctial elements, under a perturbing acceleration ε in the r-t-h frame*:*

$$\frac{da}{dt}=\frac{2a^2}{h}\left[(P_2\sin L-P_1\cos L)\varepsilon\cos\beta\cos\alpha+\frac{p}{r}\varepsilon\cos\beta\sin\alpha\right]$$

$$\frac{dP_1}{dt}=\frac{r}{h}\left\{-\frac{p}{r}\cos L\cdot\varepsilon\cos\beta\cos\alpha+\left[P_1+\left(1+\frac{p}{r}\right)\sin L\right]\varepsilon\cos\beta\sin\alpha-P_2(Q_1\cos L-Q_2\sin L)\varepsilon\sin\beta\right\}$$

$$\frac{dP_2}{dt}=\frac{r}{h}\left\{-\frac{p}{r}\cos L\cdot\varepsilon\cos\beta\cos\alpha+\left[P_2+\left(1+\frac{p}{r}\right)\sin L\right]\varepsilon\cos\beta\sin\alpha-P_1(Q_1\cos L-Q_2\sin L)\varepsilon\sin\beta\right\}$$

$$\frac{dQ_1}{dt}=\frac{r}{2h}\left(1+Q_1^2+Q_2^2\right)\sin L\cdot\varepsilon\sin\beta$$

$$\frac{dQ_2}{dt}=\frac{r}{2h}\left(1+Q_1^2+Q_2^2\right)\cos L\cdot\varepsilon\sin\beta$$

$$\frac{dL}{dt}=\sqrt{\frac{\mu}{a^3}}-\frac{r}{h}(Q_1\cos L-Q_2\sin L)\varepsilon\sin\beta$$

The Perturbative Approach

- Assumptions:
  - Perturbing acceleration ε is very small compared to the local gravitational acceleration:

$$\varepsilon \ll \frac{\mu}{r^2}$$

  - Constant modulus and direction in the radial-transversal reference frame.

$$[\varepsilon, \alpha, \beta] = const$$

  - A system of differential equations in time is translated into a system of differential equations in true longitude:

$$\frac{d\mathbf{X}}{dt} = f(\mathbf{X}, L, \varepsilon, \alpha, \beta) \Rightarrow \frac{d\mathbf{X}}{dL} = f(\mathbf{X}, L, \varepsilon, \alpha, \beta)$$

First order expansion of Equations of Motion

- With these one could obtain a set of equations in the form:

$$\mathbf{X}' = \mathbf{X}_0' + \varepsilon \mathbf{X}_1'$$

- Which could be integrated analytically between L_0 and L, thus obtaining a first-order expansion of the variation of Equinoctial elements with respect to the reference orbit:

$$\mathbf{X} = \mathbf{X}_0 + \varepsilon \mathbf{X}_1$$

- This requires finding the primitives of the integrals in the form:

$$I_{1n}(L_F) = \int_{L_0}^{L_F} \frac{1}{(1 + P_{10}\sin L + P_{20}\cos L)^n} dL$$

$$I_{Cn}(L_F) = \int_{L_0}^{L_F} \frac{\cos L}{(1 + P_{10}\sin L + P_{20}\cos L)^n} dL$$

$$I_{Sn}(L_F) = \int_{L_0}^{L_F} \frac{\sin L}{(1 + P_{10}\sin L + P_{20}\cos L)^n} dL$$

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Analytical Solution of the Equations of Motion

- Thus the first order approximate solution of perturbed Keplerian motion takes the form:

$$a(L) = a_0 + \varepsilon a_1 = a_0 + \varepsilon \left\{ 2h_0^2 a_0^2 \cos\beta \cos\alpha \left[P_{20} I_{s2}(L_0, L) - P_{10} I_{c2}(L_0, L) \right] + 22 h_0^2 a_0^2 \cos\beta \sin\alpha I_{11}(L_0, L) \right\}$$

$$P_1(L) = P_{10} + \varepsilon P_{11}$$

$$P_2(L) = P_{20} + \varepsilon P_{21}$$

$$Q_1(L) = Q_{10} + \varepsilon Q_{11}$$

$$Q_2(L) = Q_{20} + \varepsilon Q_{21}$$

$$t(L) = t_0 + \varepsilon t_1$$

- A complete set of analytic equations parameterised on the Longitude is thus available to propagate the perturbed orbital motion, in the form:

$$\mathbf{X}(L_0 + \Delta L) = f\left(\mathbf{X}(L_0), \Delta L, \varepsilon, \alpha, \beta\right)$$

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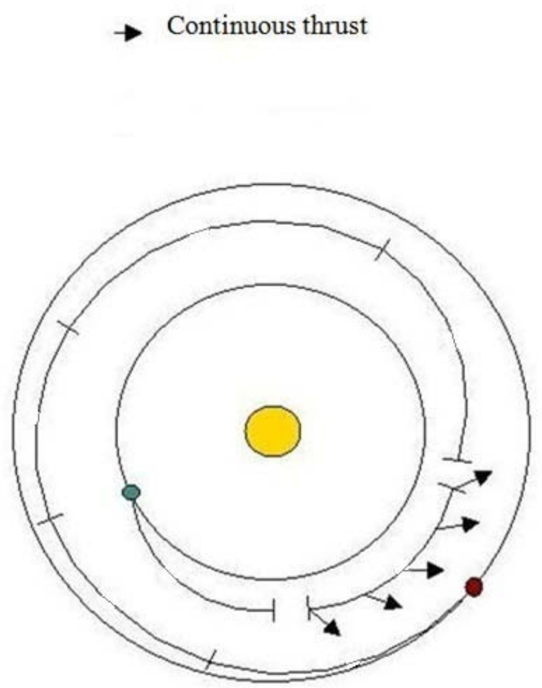
Transcription into FPET

- To propagate the motion, the trajectory is subdivided into Finite Perturbative Elements.
- On each element, thrust is continuous, albeit constant in modulus and direction in the r-t-h frame.
- ~10 times speed up compared to numerical integration and with comparable accuracy.



Deflection and System Models

Ablation Model

- The thrust is a function of the rate of mass expulsion:

$$\frac{dm_{\exp}}{dt} = 2n_{sc}v_{rot}\int_{y_0}^{y_{rot}}\int_{t_{in}}^{t_{out}}\frac{1}{H}\left(P_{in} - Q_{rad} - P_{cond}\right)dtdy$$

- The power input due to the solar concentrator is:

$$P_{in} = \eta_{sys}C_r\left(1-\varsigma_A\right)S_0\left(\frac{r_{AU}}{r_A}\right)^2$$

- The Black Body radiation loss and the conduction loss are:

$$Q_{rad} = \sigma\varepsilon_{bb}T^4 \qquad Q_{cond} = \left(T_{subl} - T_0\right)\sqrt{\frac{c_A k_A \rho_A}{\pi t}}$$

- The average velocity of the ejecta is given by:

$$\bar{v} = \sqrt{\frac{8k_B T_{subl}}{\pi M_{Mg2SiO_4}}}$$

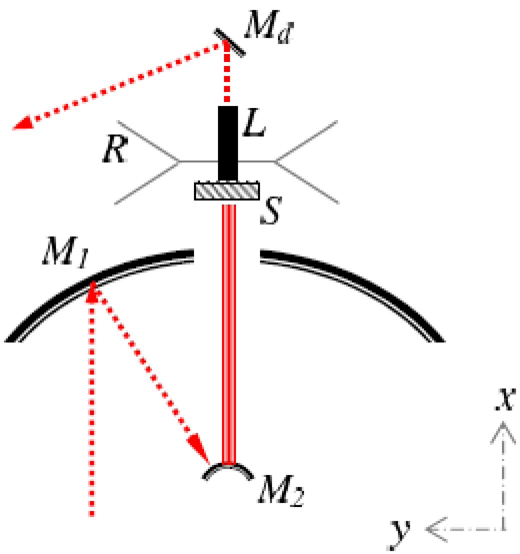
- Thus the sublimation thrust is computed, under the assumption of tangential thrust, as:

$$\mathbf{u}_{sub} = \frac{\Lambda\bar{v}\dot{m}_{\exp}}{m_A}\hat{\mathbf{v}}_A$$

Physical properties of the asteroid are known with a degree of uncertainty

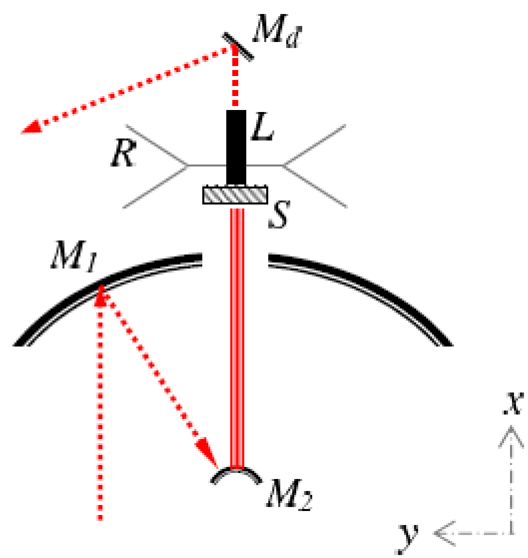
Spacecraft System sizing

- Each spacecraft consists of:
  - A primary mirror M_1 which focuses the solar rays on the secondary mirror M_2.
  - A set of solar arrays S, which collect the radiation from the secondary mirror.
  - A semiconductor laser L.
  - A steering mirror M_d, which directs the Laser light on the target.
  - A set of radiators, which dissipate energy to maintain the Solar arrays and the Laser within acceptable limits.



Spacecraft System sizing

- System sizing procedure:
  - The number of spacecraft n_{sc}, the primary mirror diameter d_{M1} and the mirror concentration ratio C_r are specified as design parameters.
  - The radiator area is computed through steady state thermal balance from the solar input power and the irradiated power.



  - The total mass of the spacecraft: $m_{sc} = m_{dry} + 1.1 m_p$
  - The dry mass: $m_{dry} = 1.2\left(m_C + m_S + m_M + m_L + m_R + m_{bus}\right)$

$$m_L = 1.5\rho_L P_L \eta_L \qquad m_M = 1.25\rho_M\left(A_d + A_{M_1} + 2A_{M_2}\right)$$

$$m_S = 1.15\rho_S A_S \qquad m_R = \rho_R A_R \qquad \eta_{sys} = \eta_L \eta_{SA} \eta_P \varepsilon_M$$

These quantities are the result of assumptions on technological readiness

Evidence-Based Robust Design

Introduction to Evidence-based Reasoning (1)

- Evidence Theory could be viewed as a generalisation of classical Probability Theory.
- Both aleatory (stochastic) and epistemic (incomplete knowledge) uncertainty can be modelled.
- Uncertain parameters **u** are given as intervals Up and a probability m is associated to each interval.

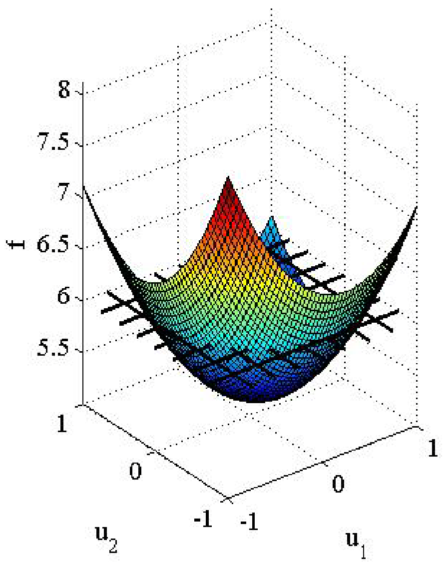
$$U_p = \left\{ \forall p : p \in [\underline{p}, \overline{p}] \right\}; \quad m(U_p) \in [0,1]$$

$$m(U_{p1}) + m(U_{p2}) + m(U_{p1} \cup U_{p2}) = 1$$

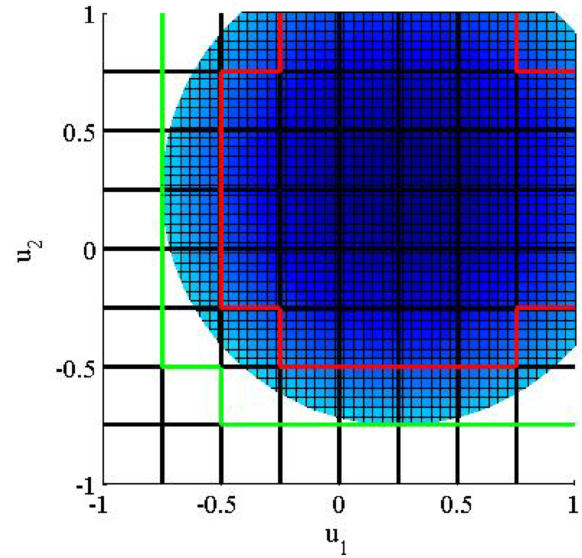
- Different uncertain intervals can be disconnected from each other or even overlapping.

Introduction to Evidence-based Reasoning (2)

- Evidence Theory uses two measures to characterise uncertainty on a given result: *Belief* and *Plausibility*. On the contrary, Probability Theory uses on the Probability of an event.

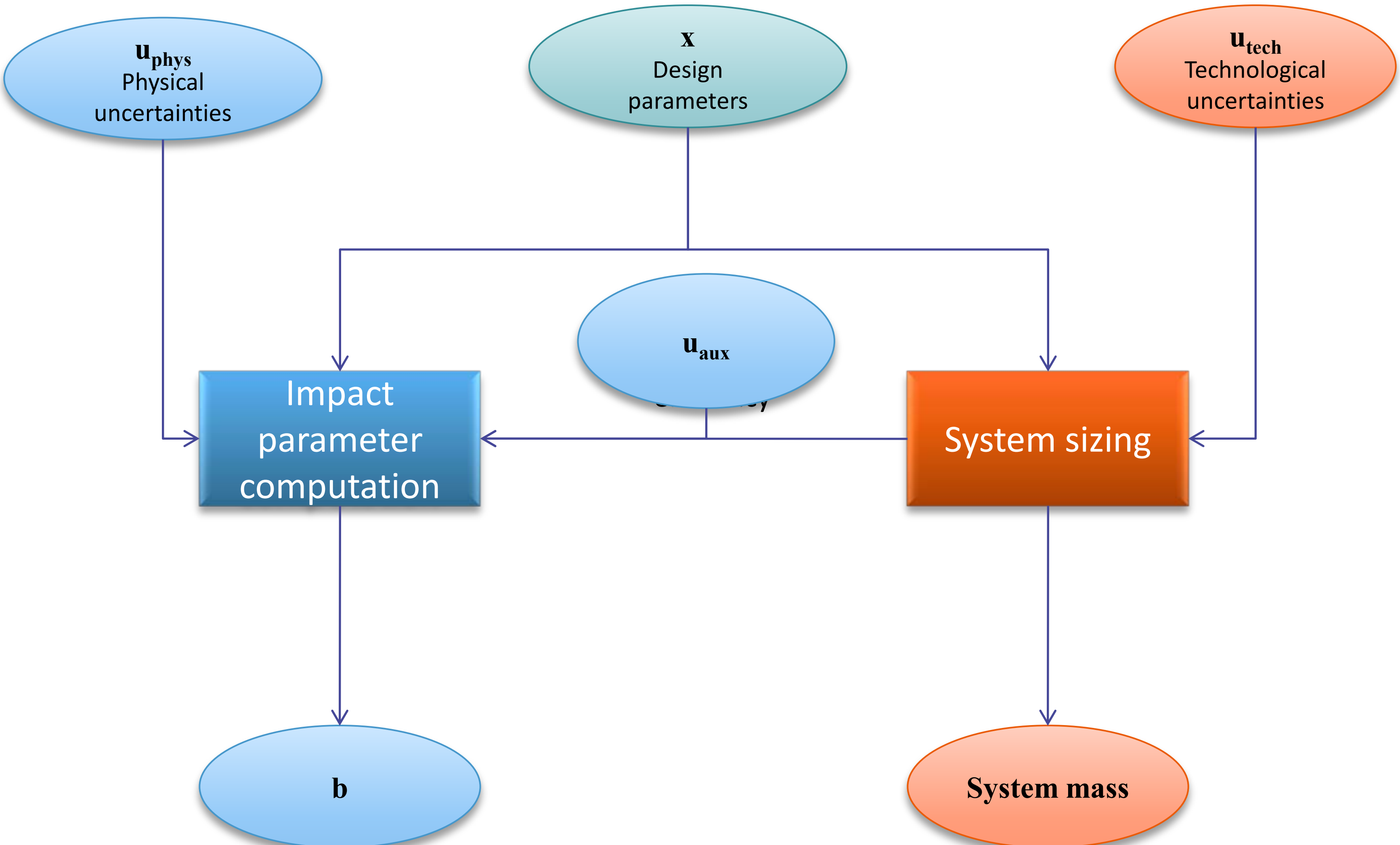


- Bel
- Pl



- *Bel* and *Pl* could be interpreted as the lower and upper bound on the likelihood of an event.

Deflection and System Model Coupling

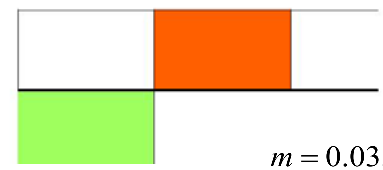


Experts' Information Fusion

- Confidence statements on uncertain parameters can have different and often conflicting sources, which need to be combined together into a single set of uncertain intervals.
- Example: three different experts express an opinion on the values for η_L :

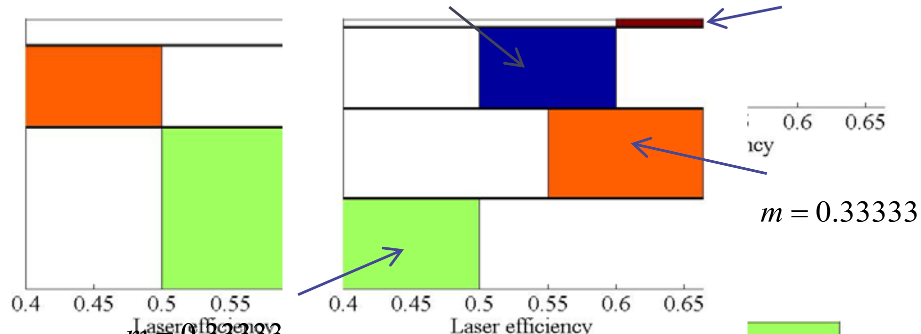
1. Conservative opinion: *"The Laser efficiency will be between 40% and 50% with 70% confidence and between 50% and 60% with 30% confidence".*

   $U_{1a}=[0.4,0.5]$ $m(U_{1a})=0.7$
   $U_{1b}=[0.5,0.6]$ $m(U_{1b})=0.3$



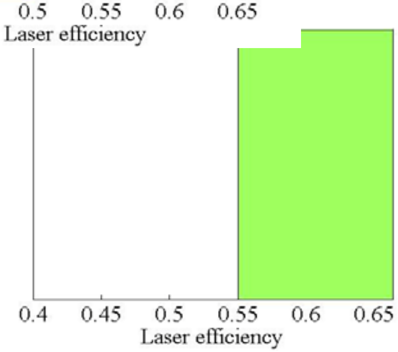
2. Realistic opinion: *"The Laser e 40% and 50% with 30% confid 60% with 60% confidence and with 10% confidence".*

   $U_{2a}=[0.4,0.5]$ $m(U_{2a})=0.3$
   $U_{2b}=[0.5,0.6]$ $m(U_{2b})=0.6$
   $U_{2c}=[0.6,0.664]$ $m(U_{2c})=0.1$



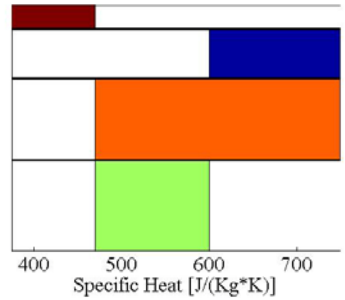
3. Optimistic opinion: *"The Laser efficiency will be between 55% and 66.4% with 100% confidence".*

   $U_3=[0.55,0.664]$ $m(U_3)=1$

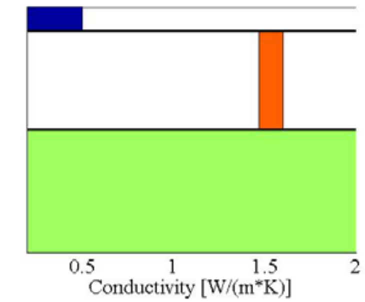


Interval summary (1): asteroid physical characteristics

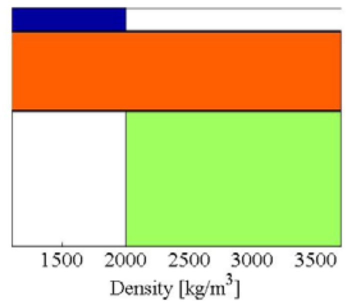
- Specific heat:



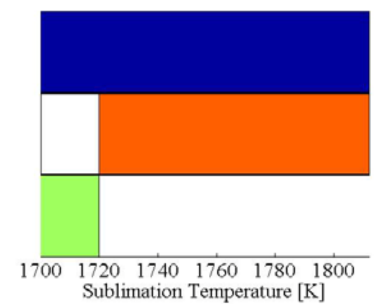
- Thermal conductivity:



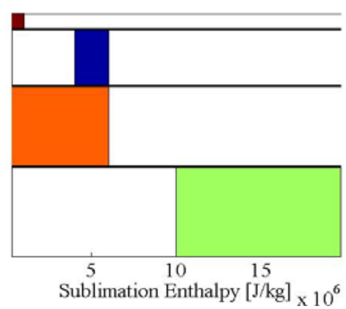
- Density:



- Sublimation Temperature:



- Sublimation enthalpy:



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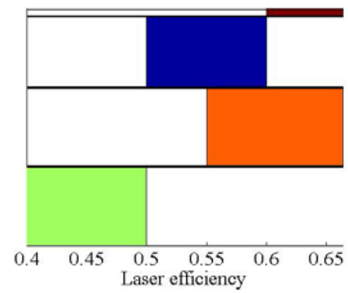
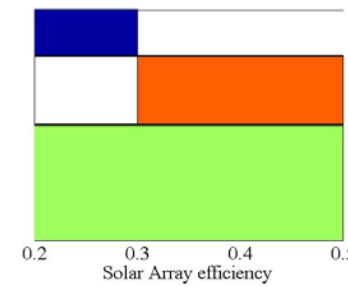
Interval summary (2): technological properties

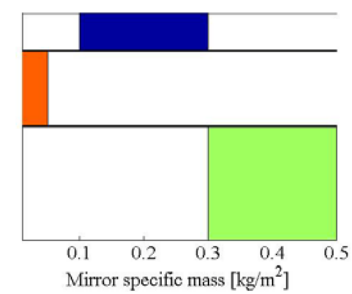
- Laser efficiency:



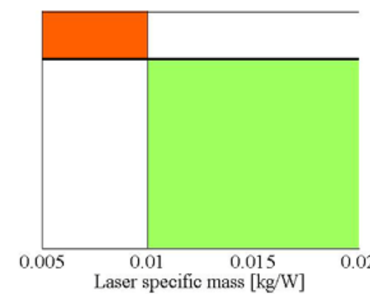
- Solar array efficiency:



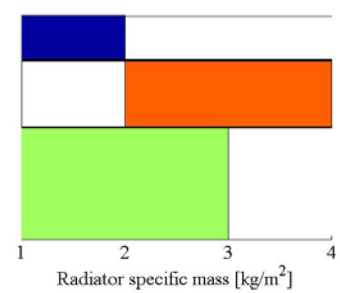
- Mirror specific mass:



- Laser specific mass:



- Radiator specific mass:



Integrated System and Trajectory Optimisation

- Minimum total spacecraft mass and maximum impact parameter variation:

$$\min_{\mathbf{x}\in D}\left[m_{system} \quad -b\right]$$

- Where $\mathbf{x}$ is given by the 3 design parameters:
    - Diameter of the primary mirror: $d_m \in [2, 20]m$
    - Number of spacecraft's in the formation: $n_{SC} \in [1, 10]$
    - Concentration ratio: $C_r \in [1000, 3000]$

- Mixed integer-nonlinear multiobjective optimisation problem
- Solution with Multi-Agent Collaborative Search (MACS) a hybrid memetic stochastic optimiser.

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Integrated System and Trajectory Optimisation Under Uncertainty

- Collection of focal elements are mapped into a unit hypercube $\bar{U}$
- The maximum over the hypercube defines the worst case values of the cost functions under uncertainty.
  - "minmax", i.e. optimised worst case scenario

$$\min_{\mathbf{x}\in D}\left[\max_{\mathbf{u}\in\bar{U}} m_{system} \quad \max_{\mathbf{u}\in\bar{U}}\left(-b\right)\right]$$

- The minimum over the hypercube defines the best case values of the cost functions under uncertainty.
  - "minmin", i.e. optimised best case scenario

$$\min_{\mathbf{x}\in D}\left[\min_{\mathbf{u}\in\bar{U}} m_{system} \quad \min_{\mathbf{u}\in\bar{U}}\left(-b\right)\right]$$

- Minimax mixed integer nonlinear programming problems. Solution with minmax version of MACS.

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Integrated System and Trajectory Optimisation Under Uncertainty

- The solution of the two problems provides the interval of optimal values for the cost functions and design parameters.

- Upper limit corresponds to maximum Belief:

$$\bar{\mathbf{y}} = [\bar{\mathbf{x}}, \bar{\mathbf{u}}] = \arg\min_{\mathbf{x}\in D}\left[\max_{\mathbf{u}\in\bar{U}} m_{system} \quad \max_{\mathbf{u}\in\bar{U}}(-b)\right]$$
$$Bel(\bar{\mathbf{y}}) = 1$$

- Lower limit corresponds to minimum Plausibility:

$$\underline{\mathbf{y}} = [\underline{\mathbf{x}}, \underline{\mathbf{u}}] = \arg\min_{\mathbf{x}\in D}\left[\min_{\mathbf{u}\in\bar{U}} m_{system} \quad \min_{\mathbf{u}\in\bar{U}}(-b)\right]$$
$$Pl(\underline{\mathbf{y}}) = 0$$

- All optimal design values under uncertainty are within these two limits.

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Results

Deterministic vs Robust

- Deterministic multi-objective optimization problem:

$$\min_{\mathbf{x}\in D}\left[m_{system},\ -b\right]$$

- “minmax” case:

$$\min_{\mathbf{x}\in D}\left[\max_{\mathbf{u}\in U}\left(m_{system}\right),\ \max_{\mathbf{u}\in U}\left(-b\right)\right]$$

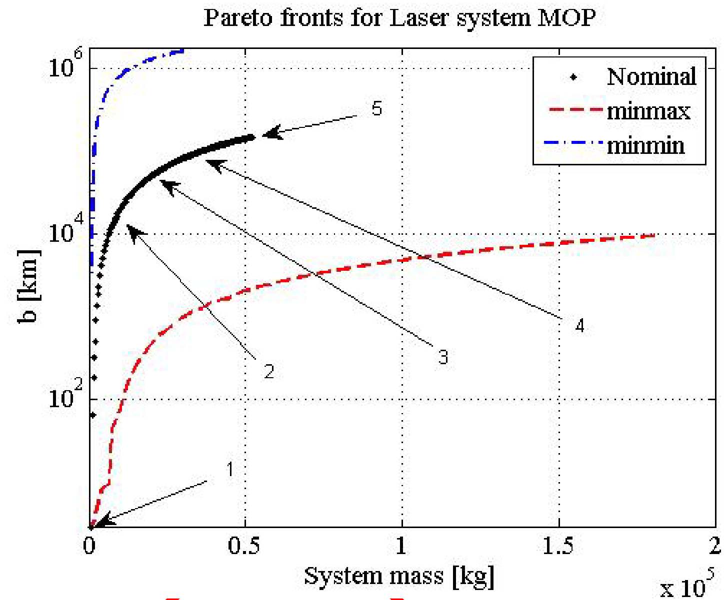
- “minmin” case:

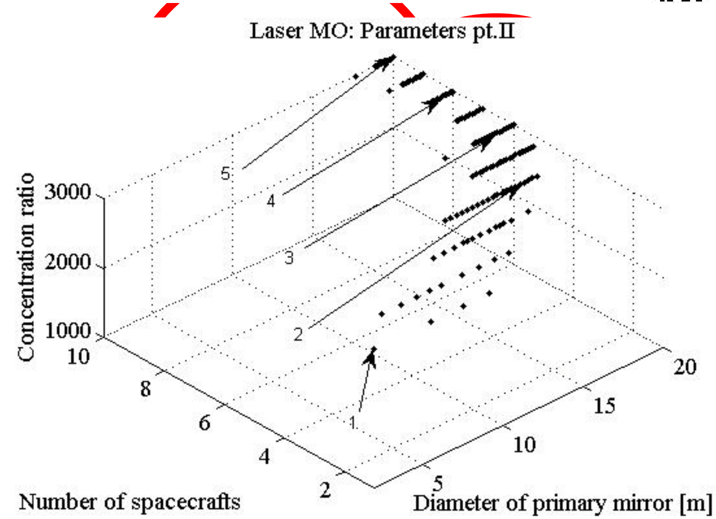
$$\min_{\mathbf{x}\in D}\left[\min_{\mathbf{u}\in U}\left(m_{system}\right),\ \min_{\mathbf{u}\in U}\left(-b\right)\right]$$

- The Pareto Sets show a switch between two families of designs:
  - In the “minmax” case, solutions with a high number of spacecraft and a small primary mirror are preferred (Many spacecraft to compensate for their low individual efficiency).
  - In the “minmin” case, solutions with a low number of spacecraft and a large primary mirror are preferred (Few spacecraft but very efficient).

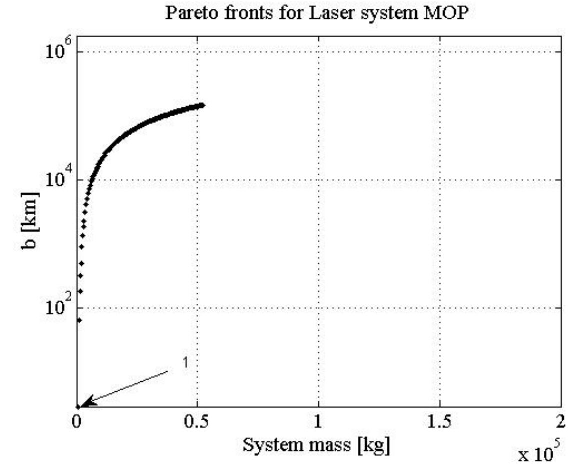
Performance parameters could be significantly sensitive to uncertainties on physical and technological parameters

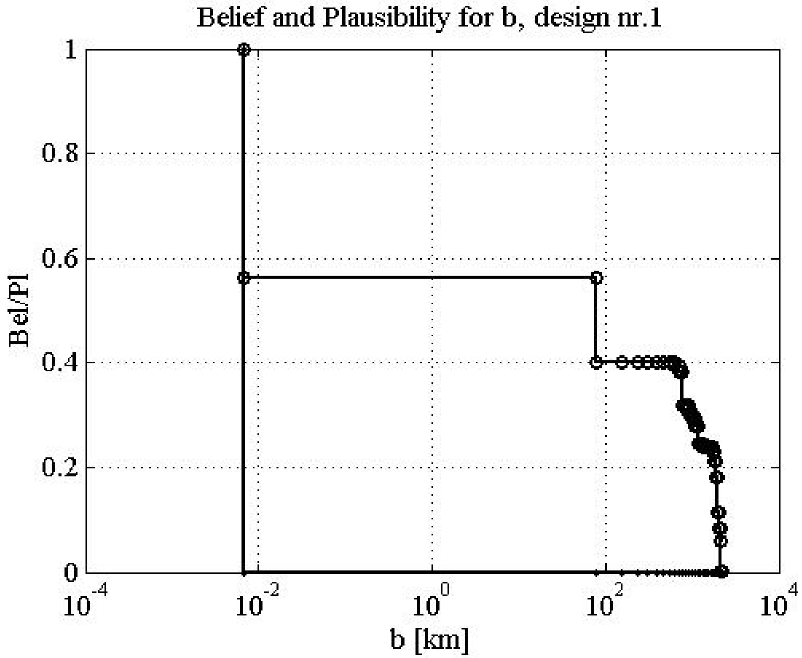
Five design points are selected for further analysis.

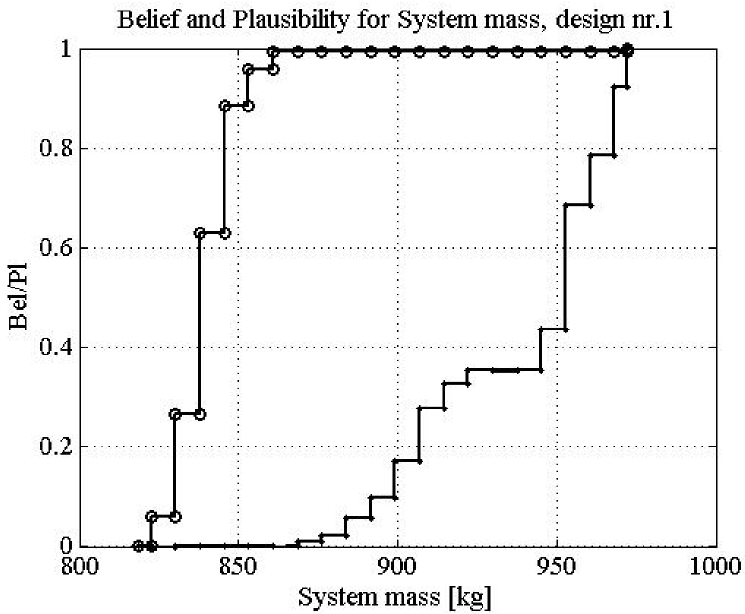




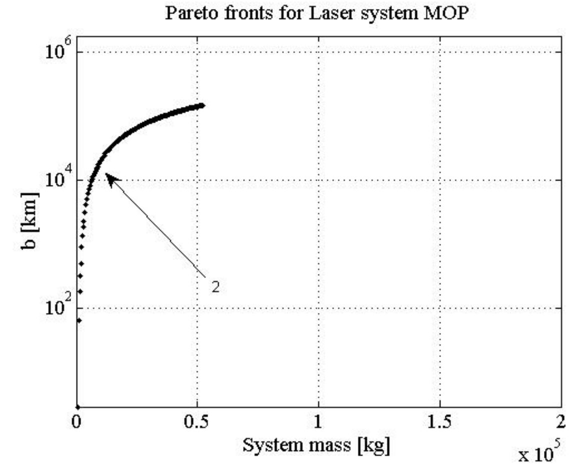
Belief/Plausibility curves: Design 1

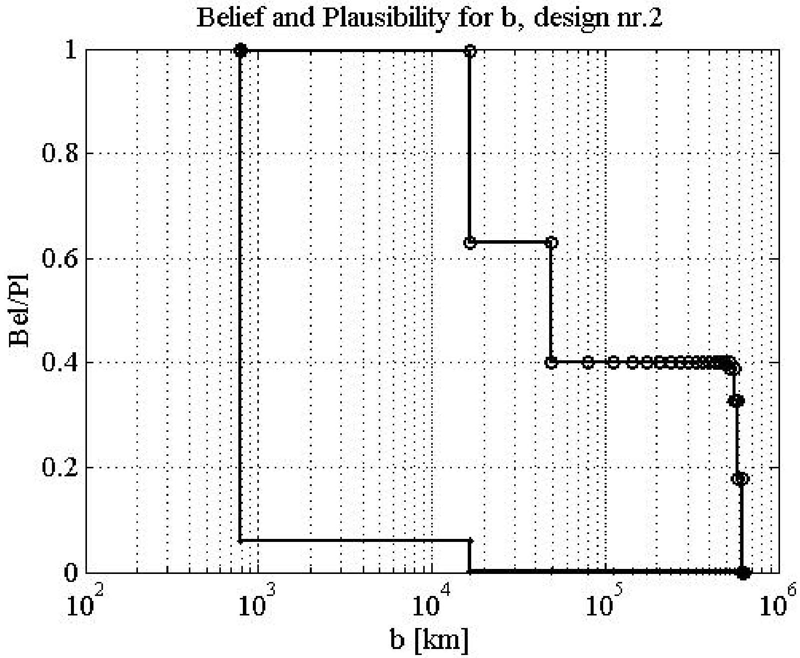


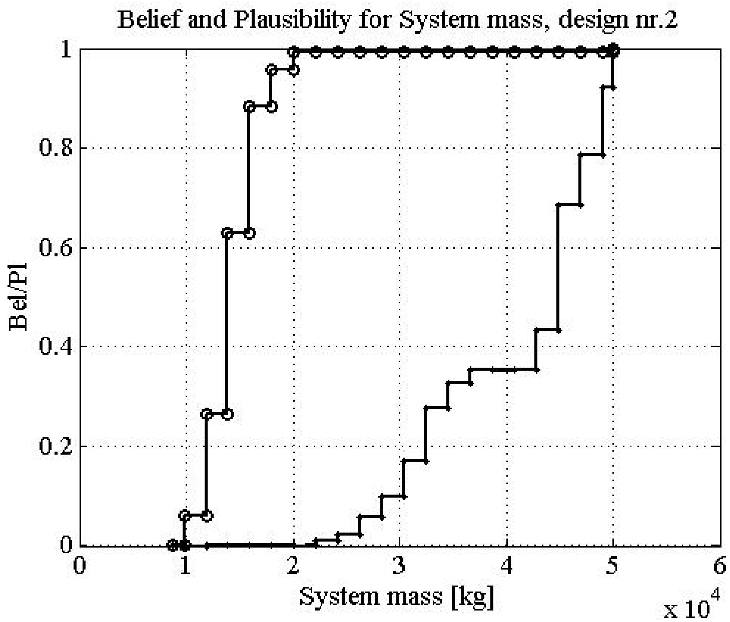




Belief/Plausibility curves: Design 2







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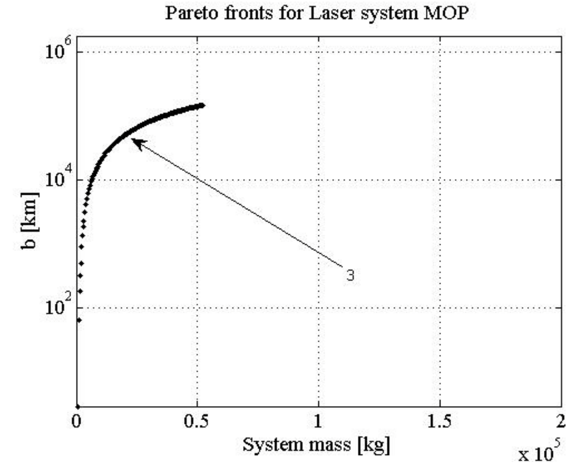
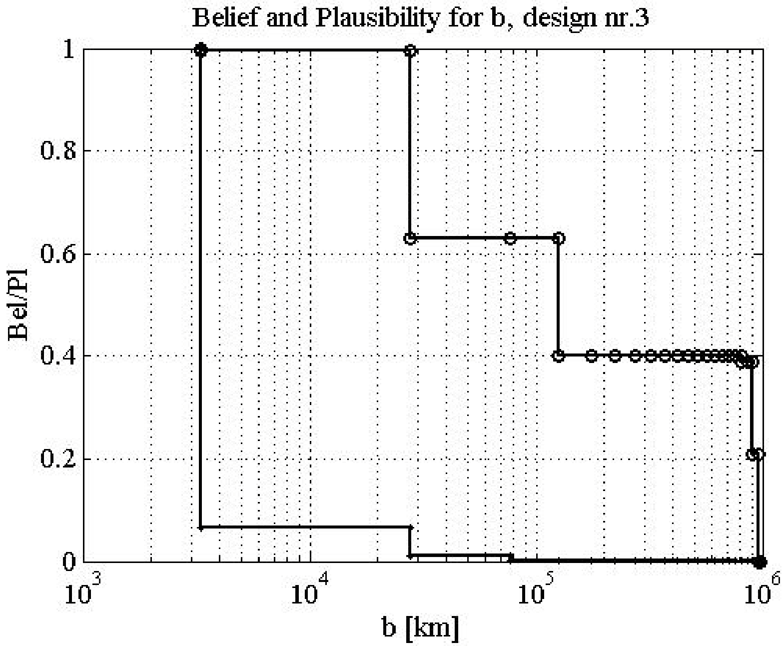
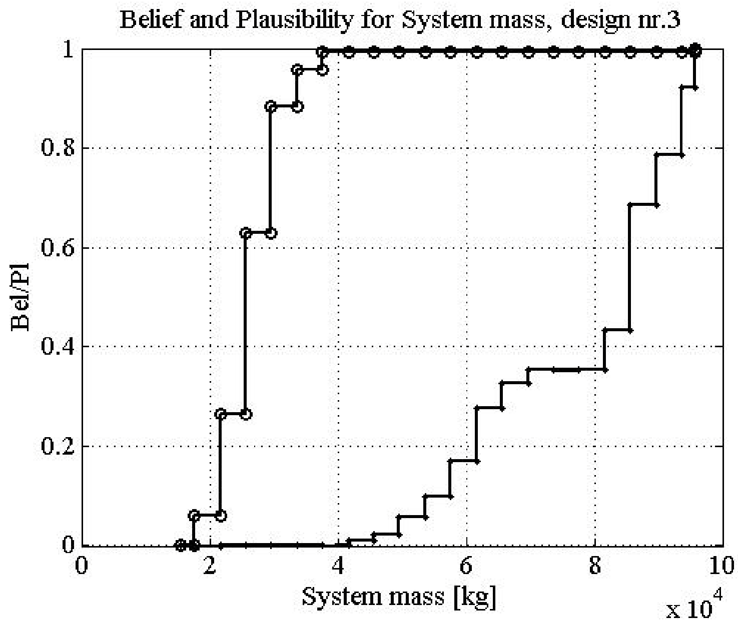
Belief/Plausibility curves: Design 3







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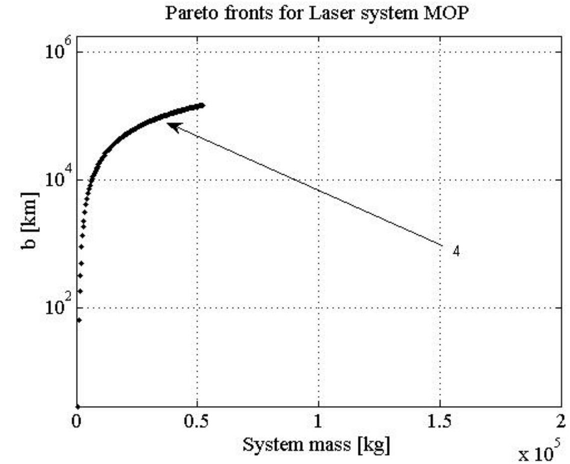
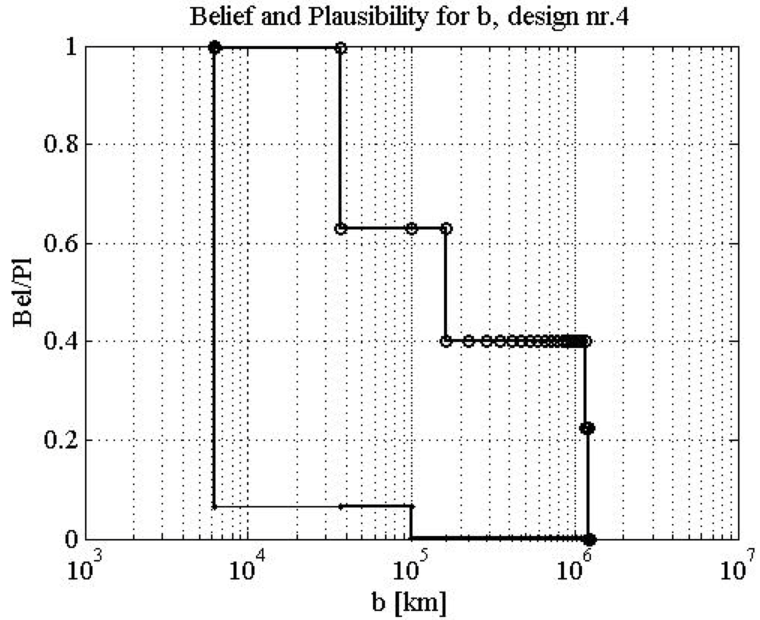
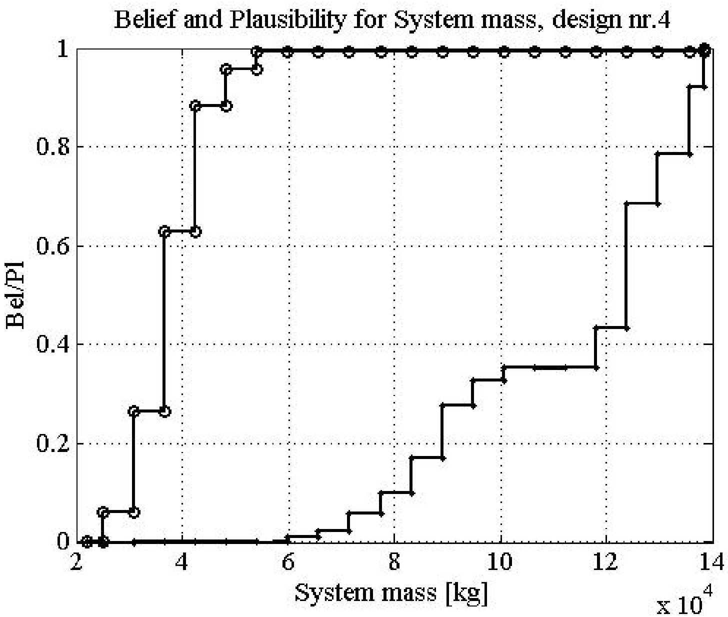
Belief/Plausibility curves: Design 4







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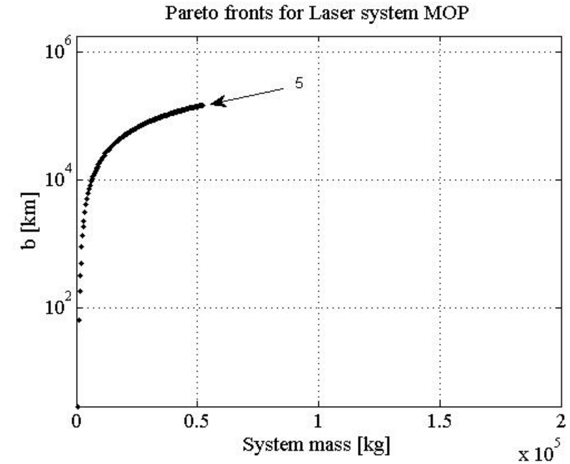
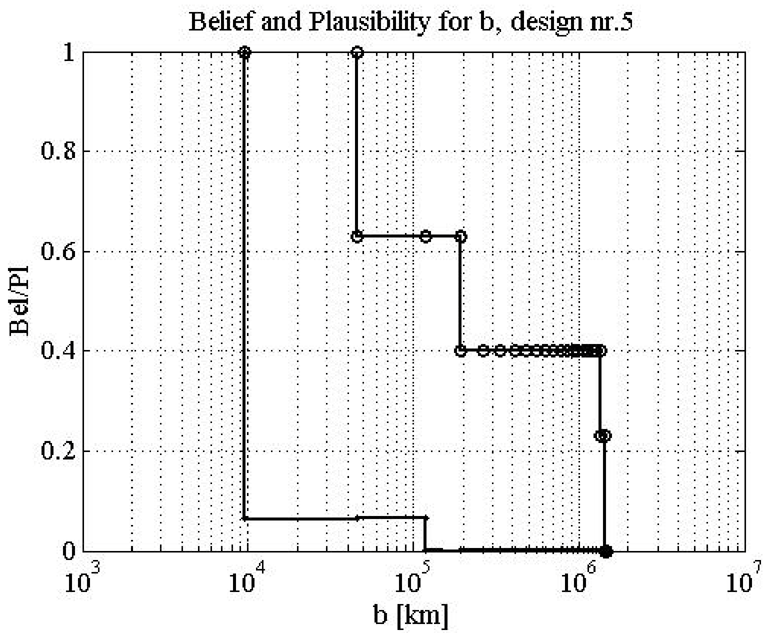
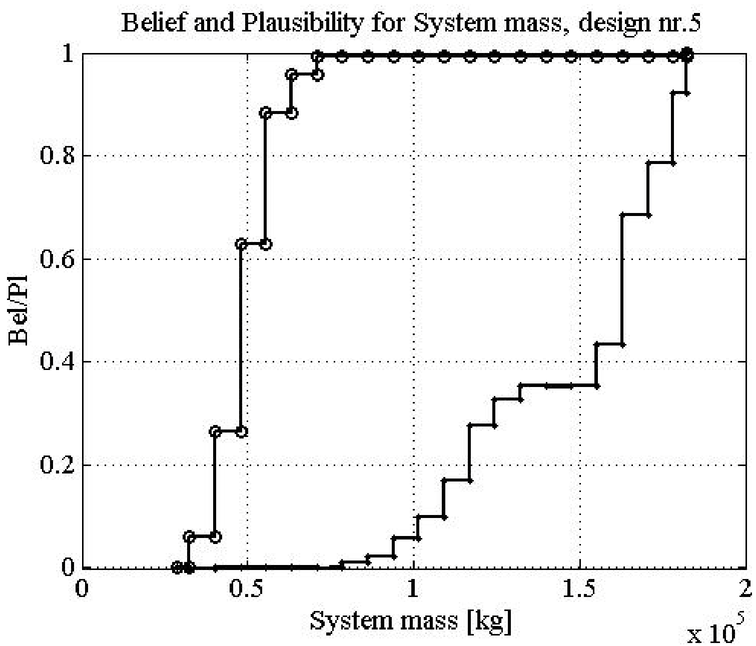
Belief/Plausibility curves: Design 5







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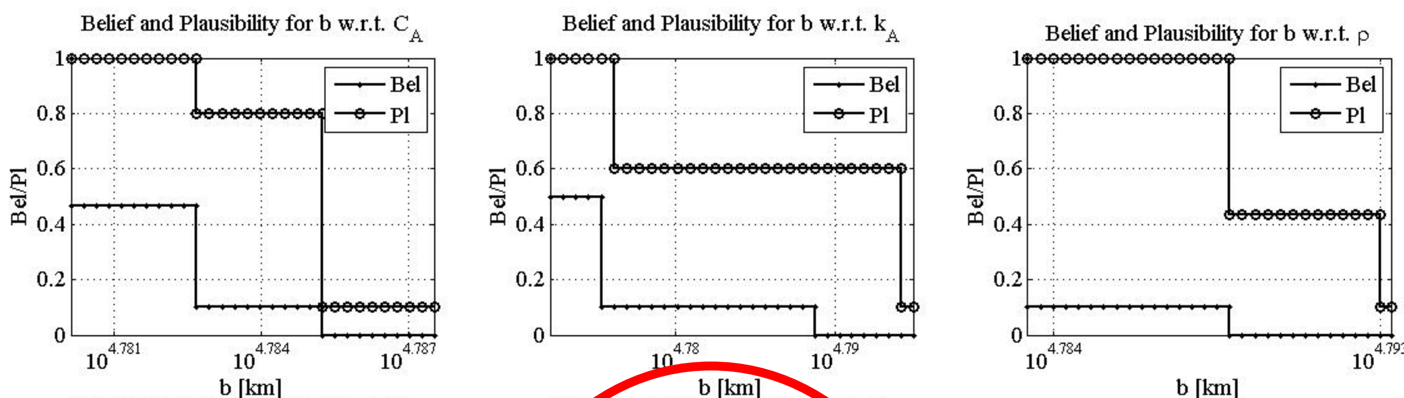
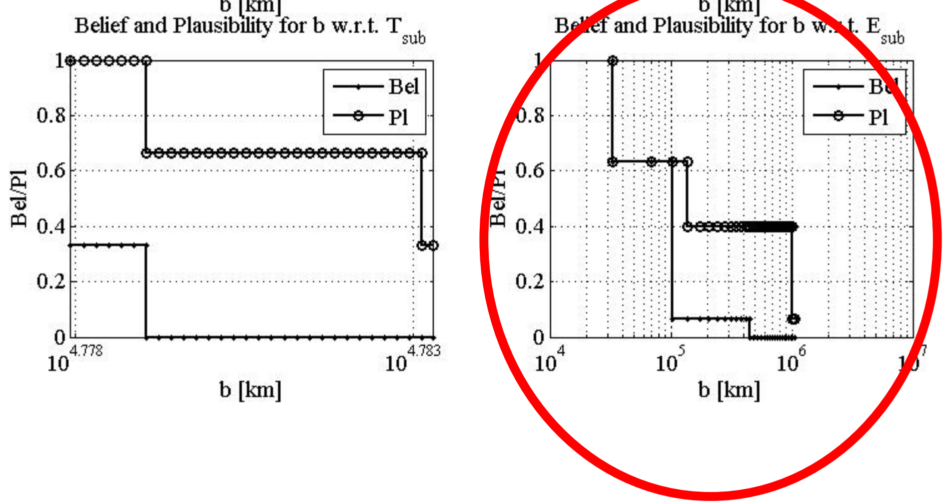
Belief/Plausibility b curves for single uncertain parameter





- The difference between ν_{min} and ν_{max} is some orders of magnitude larger in the case of the Sublimation Enthalpy.

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Conclusions

Conclusions and future work

- A detailed model for the integrated design of a Laser deflection system was proposed.
- The use of Perturbative expansion of Gauss' Variational Equations allowed for the fast integration of the dynamics of orbital deflection.
- Epistemic uncertainties were introduced by means of an Evidence Theory
- Efficient Bel/Pl reconstruction with evolutionary approach
- Future works will address the topic of optimizing the design in order to achieve adequate system robustness.

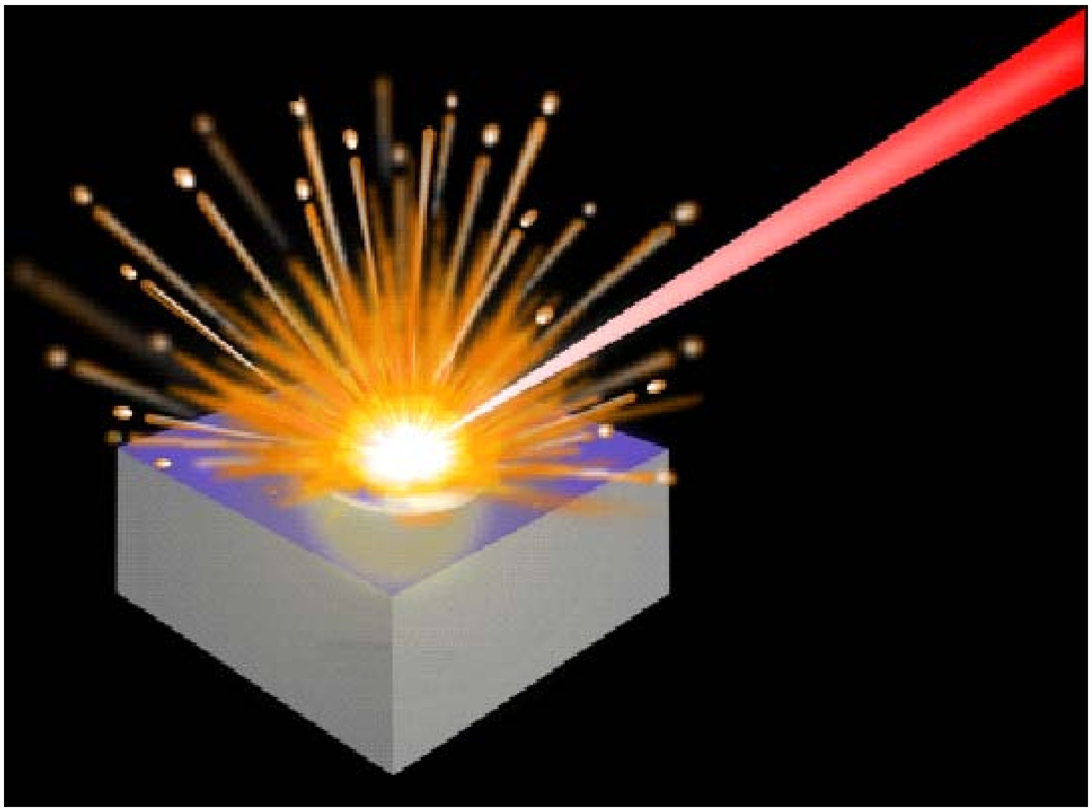
Thank you for your attention! Questions?

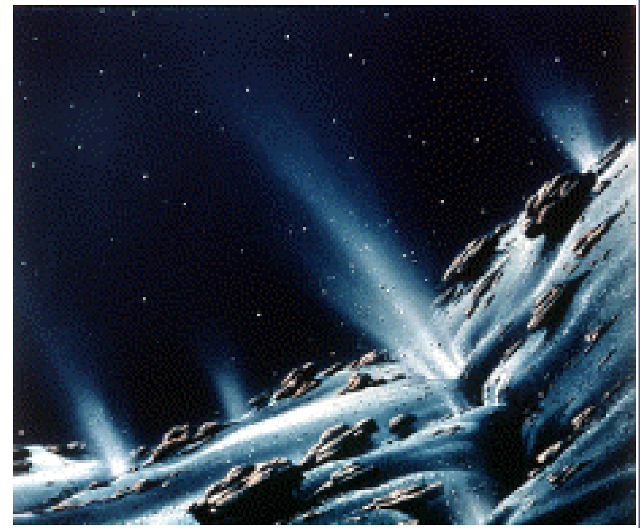
ROBUST DESIGN OF DEFLECTION ACTIONS FOR NON-COOPERATIVE TARGETS

- Deflection of non-cooperative targets is a recent and challenging research field.
- Defines the techniques which are aimed at changing the orbital parameters of a inert object (i.e. “non-cooperative). The target object could be a small celestial body, space debris etc.
- Main focus: deflection of Near Earth Objects (NEO) from Earth-threatening trajectories.
- Various NEO deflection techniques have been investigated (kinetic impactors, gravitational tug, thermonuclear explosive devices, laser ablation etc).
- Recent studies (see Vasile, Maddock, Colombo, Sanchez et al.) have identified solar-pumped laser ablation as one of the most promising deflection techniques.

ROBUST DESIGN OF DEFLECTION ACTIONS FOR NON-COOPERATIVE TARGETS

Laser ablation is achieved by irradiating the surface by a laser light source. The resulting heat sublimates the surface, transforming it directly from a solid to a gas .

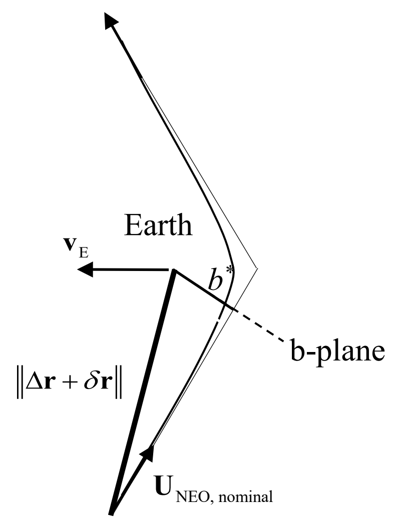




Following ablation expanded jets of ejecta -gas, dust and particles -are created. This creates an ejecta cloud & change of momentum.

Max Impact Parameter

- As a test case, asteroid Aphophis with an Earth intercepting orbit is taken.
- The deflected orbit is assumed to be proximal to the undeviated one.
- For an Earth intercepting trajectory b* will be smaller than the Earth's radius.
- The deflection obtained is measured as the difference between the undeviated and the deviated Impact parameters b* on the undeviated b-plane at t_{MOID}.



- Define $\mathbf{k}_{A_0}$ and $\mathbf{k}_{A_{dev}}$ as the Keplerian elements of the nominal and deflected asteroid orbits.
- To compute $\mathbf{k}_{A_{dev}}$ one must integrate the Gauss' Variational equations with the ablation induced thrust acceleration.

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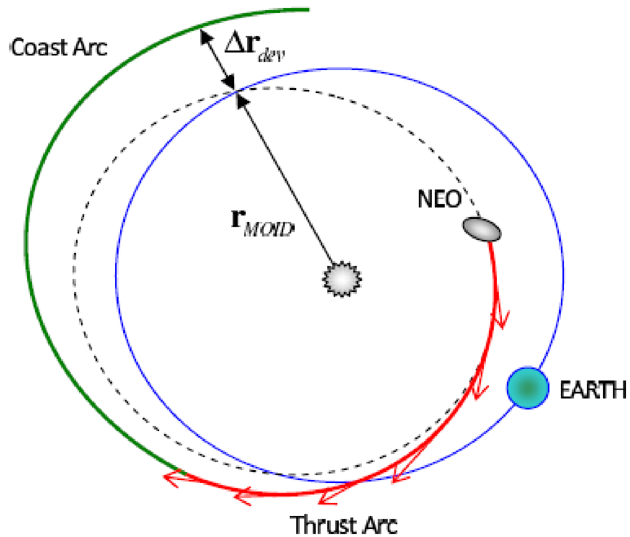
Max Impact Parameter

- The Minimum Orbital Intersection Distance (MOID) is the separation distance at the closest point between the threatening object and the Earth.
- The deflection obtained is measured as the difference between the undeviated and the deviated MOIDs at t_{MOID}.
- In the Hill reference frame, this is computed as:



$$\Delta\mathbf{r}_{dev} \Psi = \mathbf{k} r_{A_{dev}} \mathbf{k}\left({}_{A_{dev}}, {}_{A_0} \right) - \begin{bmatrix} r_{A_0} \\ 0 \\ 0 \end{bmatrix}$$

- With $\mathbf{k}_{A_0}$ and $\mathbf{k}_{A_{dev}}$ as the Keplerian elements of the nominal and deflected asteroid orbits.
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Introduction (2)

- Evidence Theory uses two measures to characterise uncertainty on a given result: *Belief* and *Plausibility*. On the contrary, Probability Theory uses on the Probability of an event.
- Given the set of values assumed by a function f of the parameters **x**:

$$Y_v = \{ y : y = f(\mathbf{x}, \mathbf{u}) < v, \mathbf{x} \in D, \mathbf{u} \in U \}$$

- Belief and Plausibility are defined as:

$$Bel_y(Y_v) = Bel_P(f^{-1}(Y_v)) = \sum_{j \in I_B} m_P(U_j)$$

$$Pl_y(Y_v) = Pl_P(f^{-1}(Y_v)) = \sum_{j \in I_P} m_P(U_j)$$

- Where:

$$I_B = \{ j : U_j \subset f^{-1}(Y_v) \}$$

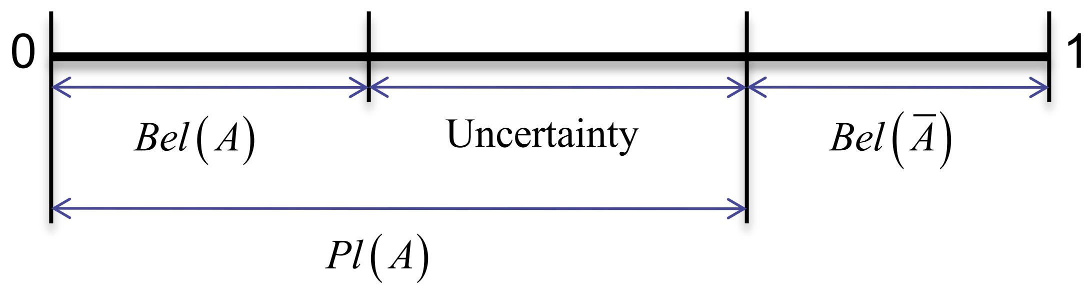
$$I_P = \{ j : U_j \cap f^{-1}(Y_v) \neq 0 \}$$

- *Bel* and *Pl* could be interpreted as the lower and upper bound on the likelihood of an event.

Introduction (3)

- Differently from the probability of an event and its contrary, *Bel* and *Pl* are not strictly complementary.
- Instead, the following relationships are valid:

$$Bel(A)+Bel(\overline{A})\le 1 \qquad Pl(A)+Pl(\overline{A})\ge 1 \qquad Bel(A)+Pl(\overline{A})=1$$



Belief and Plausibility curves reconstruction

- For a given design point $\mathbf{x}$, we want to reconstruct the Belief and Plausibility curves for the mass and MOID, with respect to the uncertain parameters $\mathbf{u}$.

$$y^* \in Y \to Bel\left(y \le y^*\right)$$
$$y^* \in Y \to Pl\left(y \le y^*\right)$$

  Where Y is the domain of the admissible values for the performance parameter $y=f(\mathbf{x},\mathbf{u})$.

- The computation of mass and MOID curves are uncoupled and treated separately.
  - Uncertainties on technological and physical parameters can be treated separately.
  - Some variables which are a function of the system sizing and contribute to the MOID computation could be treated as uncertain parameters as well.

Interval combination

- We obtain three matrices:

$$A_1 = \begin{bmatrix} 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad A_2 = \begin{bmatrix} 0.3 & 0 & 0 & 0 \\ 0 & 0 & 0.6 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.1 \end{bmatrix} \quad A_3 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

- Which could then be averaged:

$$\bar{A} = mean\left(A_i\right) = \begin{bmatrix} 0.3333 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 0 \\ 0 & 0 & 0 & 0.3333 \\ 0 & 0 & 0 & 0.0333 \end{bmatrix}$$

- Leading to the the equivalent interval:

$$U_a = [0.4, 0.5] \quad m\left(U_a\right) = 0.3333$$
$$U_b = [0.5, 0.6] \quad m\left(U_b\right) = 0.3$$
$$U_c = [0.55, 0.664] \quad m\left(U_c\right) = 0.3333$$
$$U_d = [0.6, 0.664] \quad m\left(U_d\right) = 0.0333$$

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Interval summary (1): asteroid physical characteristics

	Interval 1			Interval 2			Interval 3			Interval 4		
	LB	UB	m	LB	UB	m	LB	UB	m	LB	UB	m
Specific Heat [J/KgK]	375	470	0.1	470	600	0.3667	470	750	0.3333	600	750	0.2
Thermal Conductivity [W/mK]	0.2	0.5	0.1	1.47	0.6	0.4	0.2	2	0.5			
Density [kg/m^3]	1100	2000	0.1	2000	3700	0.5667	1100	3700	0.3333			
Sublimation temperature [K]	1700	1720	0.3333	1720	1812	0.3333	1700	1812	0.3333			
Sublimation Enthalpy [J/kg]	2.7e5	1e6	0.0667	2.7e5	6e6	0.3333	4e6	6e6	0.2333	10e6	19.686e6	0.3667

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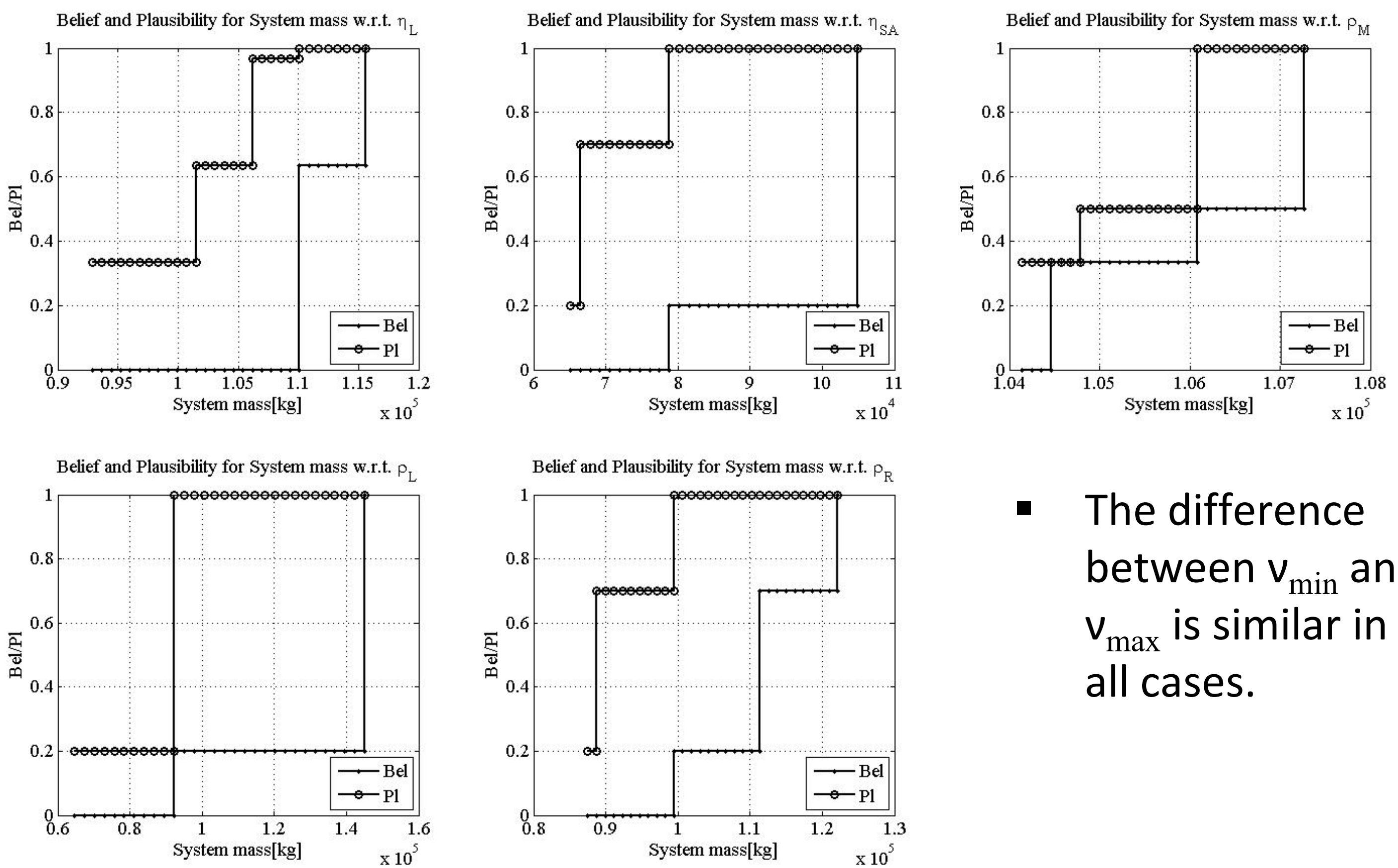
Interval summary (2): technological properties

	Interval 1			Interval 2			Interval 3			Interval 4		
	LB	UB	m	LB	UB	m	LB	UB	m	LB	UB	m
Laser efficiency	0.4	0.5	0.3333	0.5	0.6	0.3	0.55	0.664	0.3333	0.6	0.664	0.0333
Solar Array efficiency	0.2	0.3	0.2	0.3	0.5	0.3	0.2	0.5	0.5			
Mirror specific mass [kg/m^2]	0.3	0.5	0.5	0.1	0.3	0.1667	0.01	0.05	0.3333			
Laser specific mass [kg/W]	0.005	0.01	0.2	0.01	0.02	0.8						
Radiator mass [kg/m^2]	1	2	0.2	1	3	0.5	2	4	0.3			

Belief/Plausibility System Mass curves for single uncertain parameter



- The difference between ν_{min} and ν_{max} is similar in all cases.