Uncertainty-based multidisciplinary design optimization of lunar CubeSat missions

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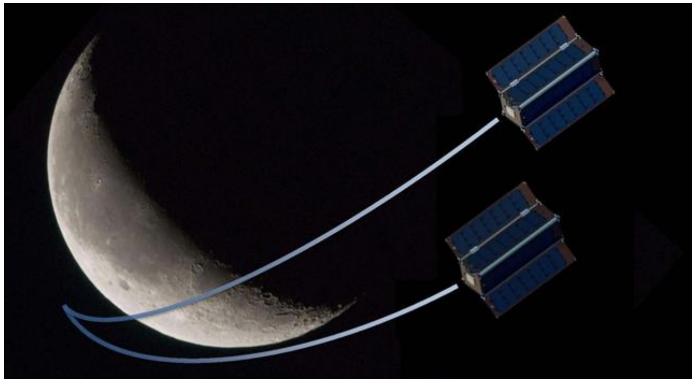
Outline

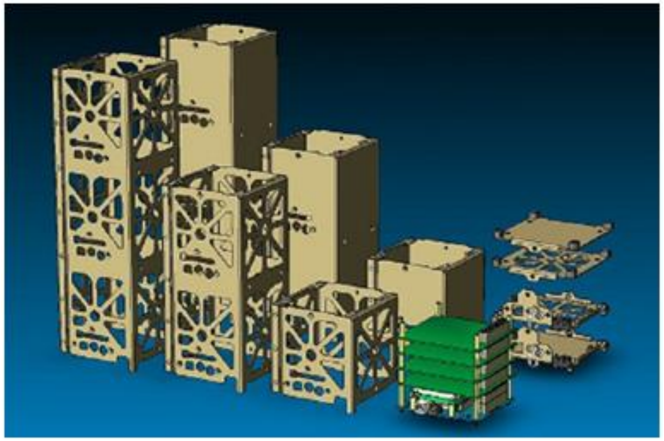
- Introduction
- Problem Formulation
- Optimization Methodology
- Results & Discussions
- Conclusions

Introduction

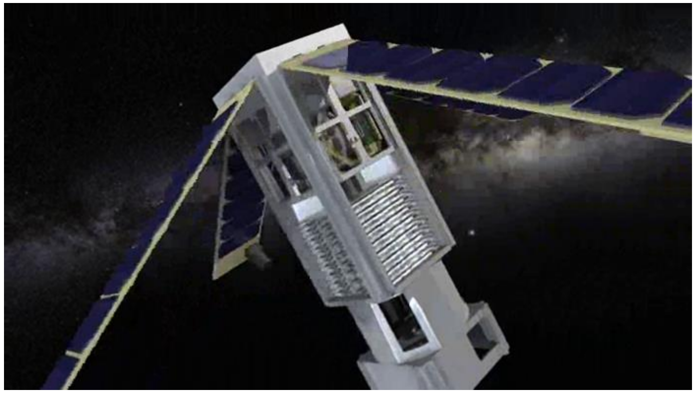
- Cost-effective shift
  - Large-scale to small-scale
  - Successful heritage, easy launch, much lower cost, faster development



Dual INSPIRE CubeSats by NASA



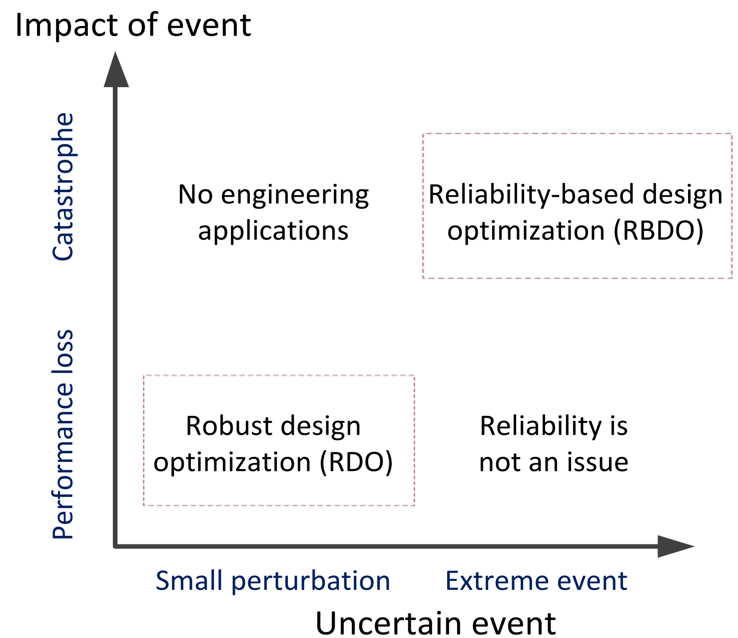
3U, 2U, 1U cubic cells



3U CubeSat by PocketSpacecraft

Introduction

- Goals of our research
  - Multidisciplinary design optimization (MDO) under uncertainty
  - Uncertainty quantification and probabilistic optimization for lunar CubeSats
  - Cost risk minimization with regard to robustness and reliability



Problem Formulation

Uncertainty

$$\tilde{f} \approx f(s,\omega)$$

Surrogate model

Design variables

Problem Formulation

- Lunar trajectory and orbit design
  - Edelbaum's analysis

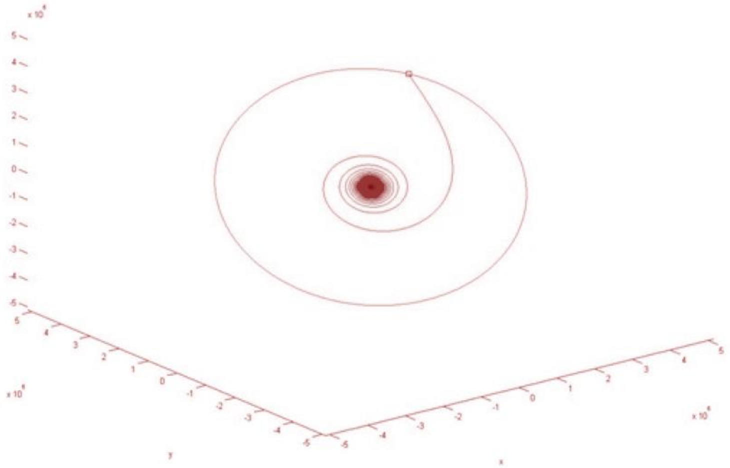
$$\Delta V = V_0 \cos\beta_0 - \frac{V_0 \sin\beta_0}{\tan(\frac{\pi}{2}\Delta i + \beta_0)}$$

$$\beta(t) = \tan^{-1}(\frac{V_0 \sin\beta_0}{V_0 \cos\beta_0 - a_T t})$$

$$V(t) = \sqrt{V_0^2 - 2V_0 a_T t \cos\beta_0 + a_T^2 t^2}$$

$$\Delta i(\mathrm{t}) = \frac{2}{\pi}[\tan^{-1}(\frac{a_T t - V_0 \cos\beta_0}{V_0 \sin\beta_0}) + \frac{\pi}{2} - \beta_0]$$

$$m_p = m_{total}(1 - e^{-\Delta V / g I_{sp}})$$



Simulated spiral trajectory

Problem Formulation

- Subsystem definition
  - Propulsion: Miniature Xenon Ion (MiXI)

Engine	Thrust (mN)	Mass (kg)	Isp (s)	Power (W)	Efficiency (%)
MiXI	0.5-3	0.2	3000	13-50	~50

Source: http://dst.jpl.nasa.gov/thrusters/

  - Key payload: CCD camera

$$D_r = \theta_x V_N \frac{hsb_{it}}{d_s{}^2 q} \qquad d_s = \mu_0 h / f_c$$

$$S_w = 2R_e \left\{ \sin^{-1}[\sin \omega_x (h + R_e) / R_e] - \omega_x \right\} / \sin i$$

  - Thermal: passive control $\sum Q_{in} - \sum Q_{out} = 0$

$$T_{sc} = \left\{ \frac{\alpha I_s [A_s F_s \cos(\theta_s) + \rho_A A_A F_A] + Q_{\text{int}} + \sigma(\varepsilon_{sp} A_{sp} + \varepsilon_R A_R) F_{sp} T_{sp}^4 + \sigma \varepsilon_{IR,sc} \varepsilon_{IR} A_{IR} F_{IR} T_{IR}^4)}{\sigma(\varepsilon_{sp} A_{sp} + \varepsilon_R A_R) F_{sp} + \sigma \varepsilon_{IR,sc} \varepsilon_{IR} A_{IR} F_{IR}} \right\}$$

Problem Formulation

- Uncertainty definition

Discipline	Parameter	Notation	Distribution
Orbit	Orbit altitude (km)	h	Truncated Nor.
	Lunar orbit inclination (deg)	i	Normal
Payload	CCD Focus length (mm)	f_c	Normal
Multiple	Mission cycle (year)	T_{life}	Normal
Propulsion	Efficiency	η_t	Normal
	Input power (kW)	P_t	Normal
	Isp (s)	I_{sp}	Normal
Power	Solar energy-conversion efficiency	η_a	Normal
	Solar array energy-mass density (W ħ/kg)	γ_a	Normal
	Average discharge depth	DOD	Normal
Multiple	System mass margin	ε_m	Interval
	System power margin	ε_p	Interval

Problem Formulation

- Reliability-based robust design optimization (RBRDO)

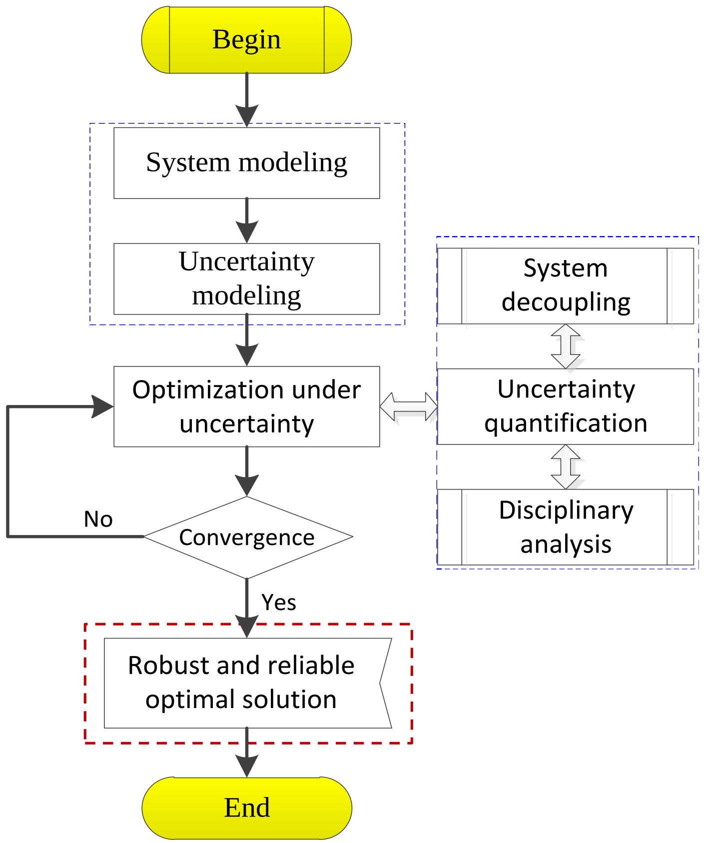
$$\begin{cases} \text{find} & \mu_{\mathbf{X}} = [\mu_h \quad \mu_i \quad \mu_{f_c} \quad \mu_{T_{life}}] \\ \min & \int f_C d\omega, \int f_M d\omega, \sqrt{\int f_C{}^2 d\omega - (\int f_C d\omega)^2} \\ \text{s.t.} & g_1 : \Pr\{d_s \le 30\text{m}\} \ge 0.99 \\ & g_2 : \Pr\{F_{str} > 1\} \ge 0.99 \\ & g_3 : \Pr\{V_{sat} \le 3U\} \ge 0.99 \\ & g_4 : \Pr\{N_{Ba} \le 10,000\} \ge 0.99 \\ & 200\text{km} \le \mu_h \le 600\text{km}, 80^\circ \le \mu_i \le 90^\circ \\ & 20\text{mm} \le \mu_{f_c} \le 200\text{mm}, 2\text{a} \le \mu_{T_{life}} \le 6\text{a} \end{cases}$$

$$f_C = C_{sat} / (D_r T_w \frac{365 L_T}{M_c}) \qquad f_M = \sum M_{\text{sub},i}$$

Optimization Methodology

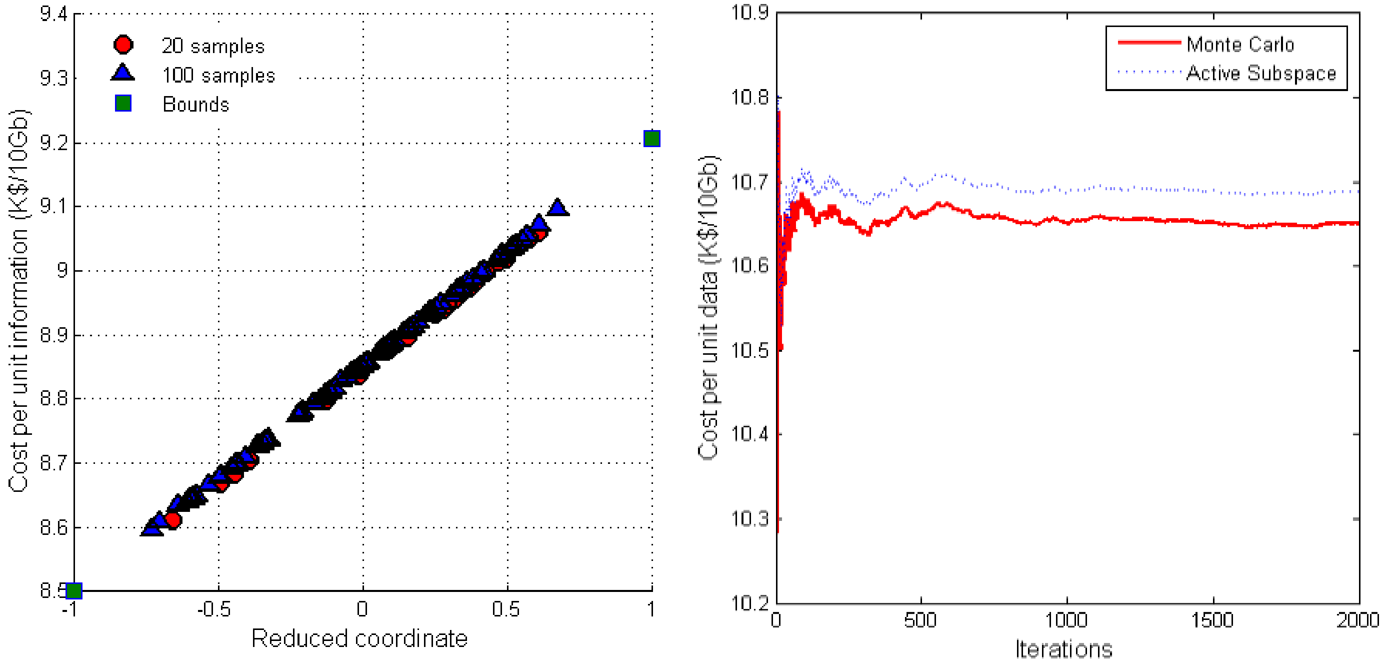
Uncertainty-based multidisciplinary design optimization of lunar CubeSat missions

- Optimization workflow



Optimization Methodology

- In-loop uncertainty quantification
  - Previous methods: Monte Carlo; polynomial chaos, compressed sensing…
  - Our method: identify a one-dimensional active subspace

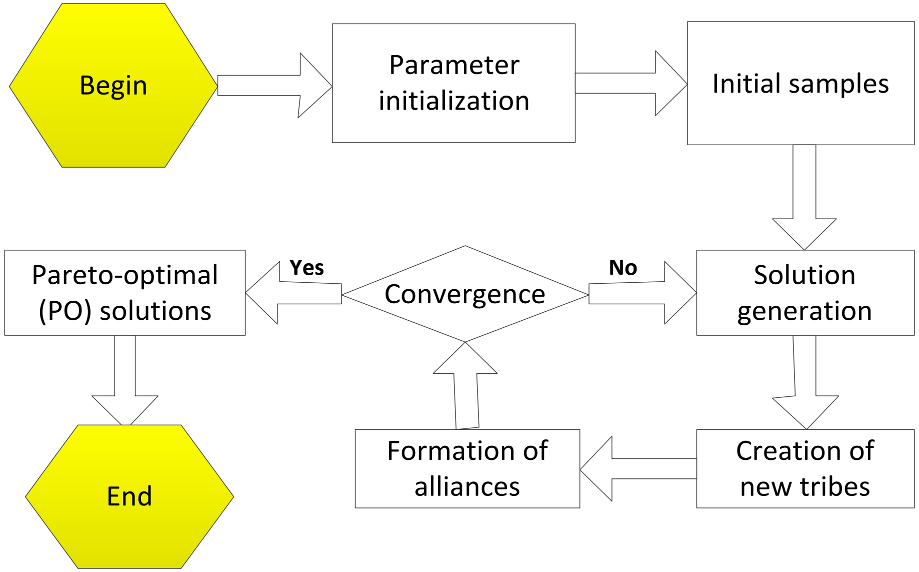


Applied to 3U lunar CubeSat

Optimization Methodology

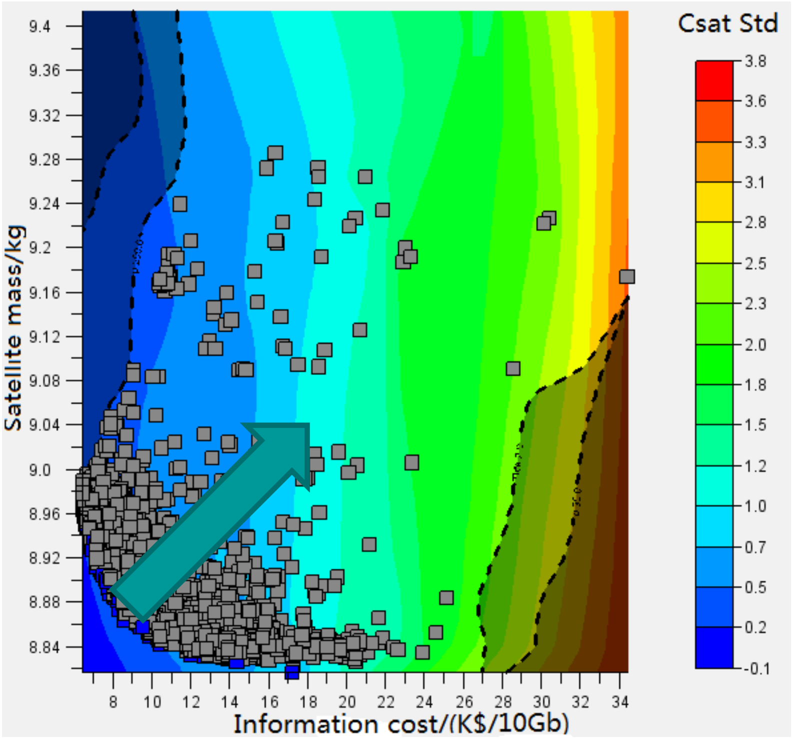
- Multi-objective solver
  - Previous algorithms: MOGA, NSGA-II, MOPS..
  - Our method:

Multi-objective alliance algorithm (MOAA)



Results & Discussions

- RBRDO solutions



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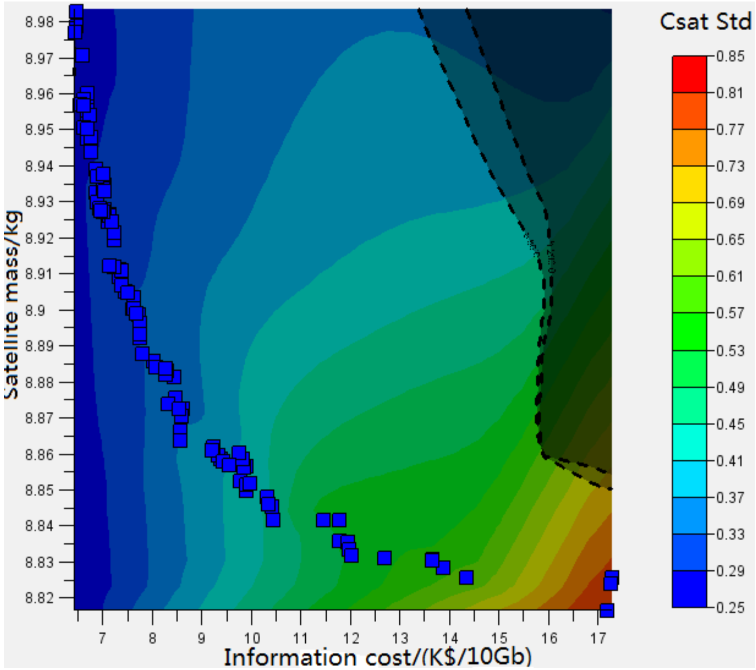
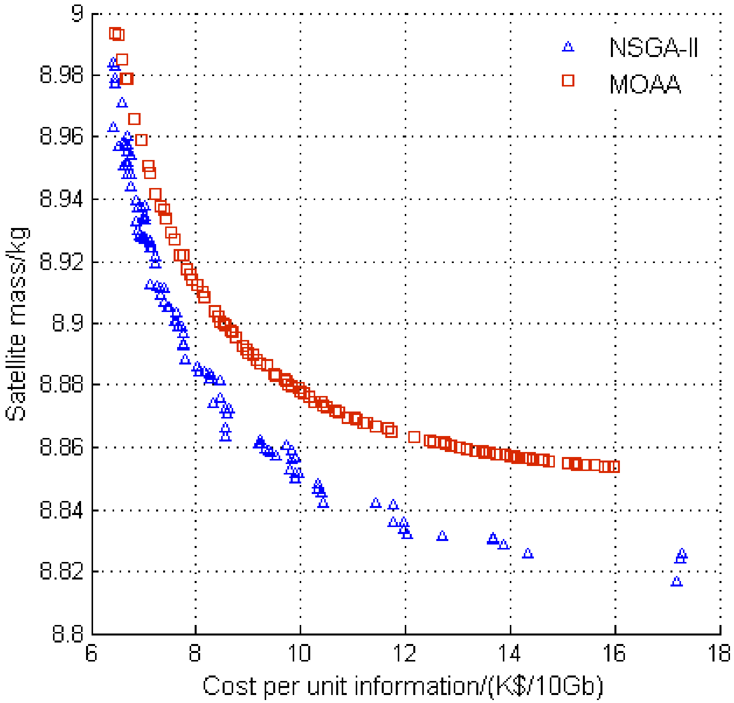
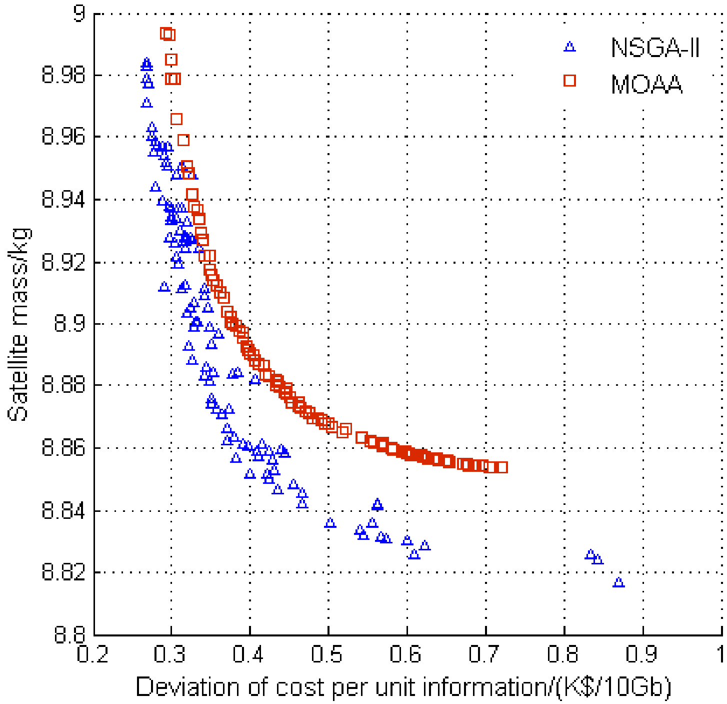


Pareto front

Results & Discussions

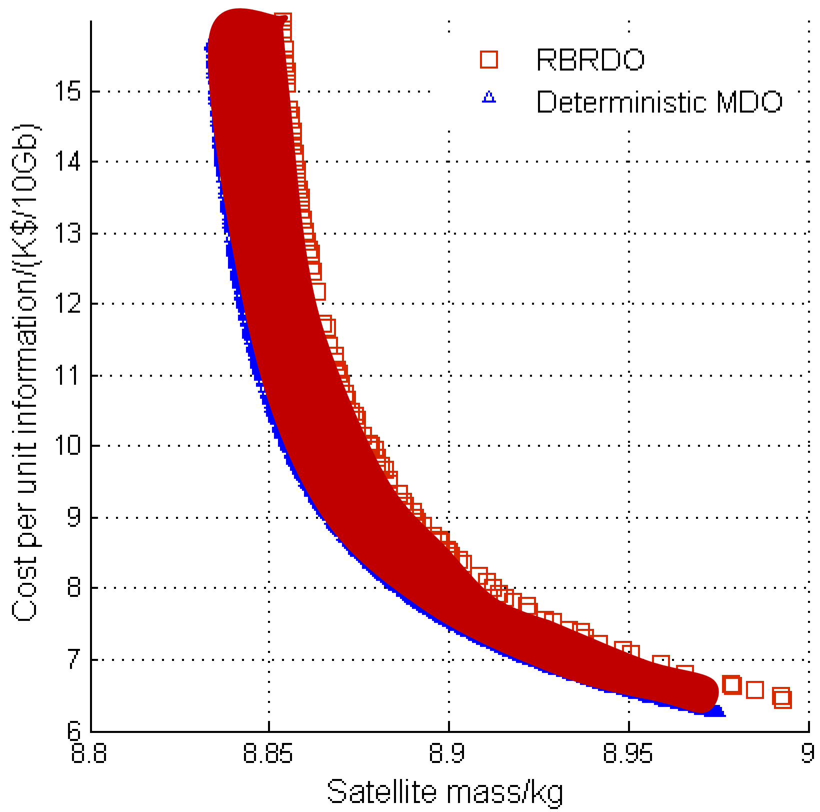
- Pareto comparison
  - MOAA vs. NSGA-II





Results & Discussions

- Deterministic vs. Nondeterministic



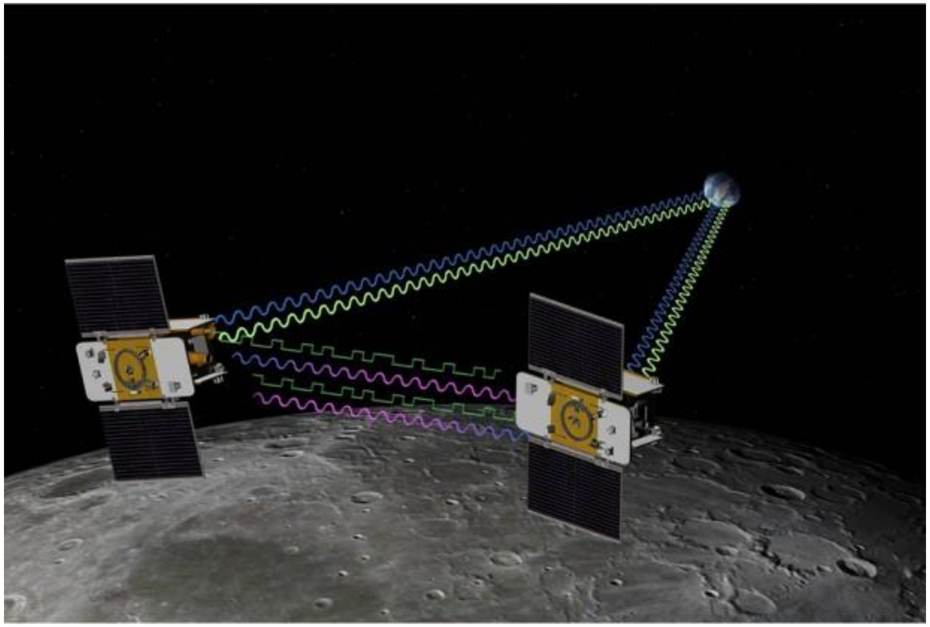
Conclusions

- Take home messages

Conclusions

- MOAA and active subspaces work.
- RBRDO worthwhile for lunar CubeSats.
- Reference for conceptual design and parameter control.
- Further perfected and demonstrated in near missions.

Thank You



CubeSat is revolutionizing aerospace science and engineering.

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