Current Methods and a Future Vision for Mission Concept Systems Development at NASA JPL

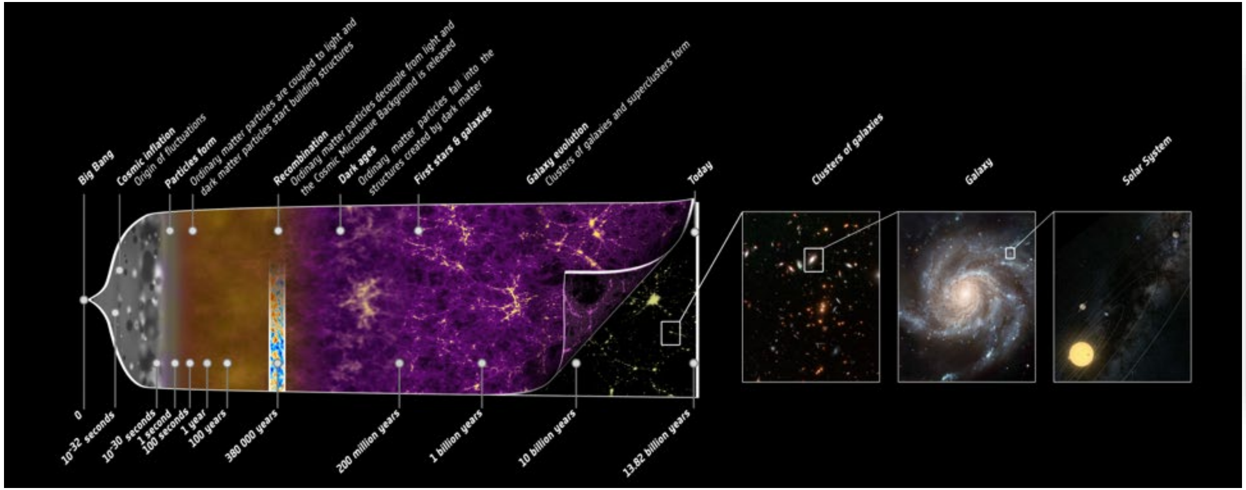
Presented by Dr. Amy Trangsrud,
Technical Group Supervisor,
Mission Concept Systems Development Group,
Jet Propulsion Laboratory,
California Institute of Technology (Caltech)

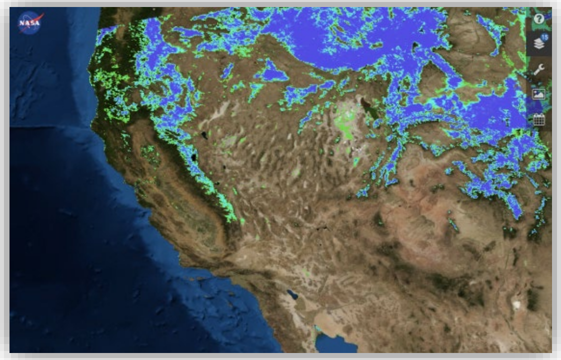
Jet Propulsion Laboratory
California Institute of Technology

Systems Engineering for Science-driven missions

System: A combination of components that work in synergy to collectively perform a useful objective

$\underbrace{\text{useful objective}}$ to advance science and/or societal benefit (science applications).





Science Systems Engineering vision: Optimize science per dollar by using robust quantitative science performance modelling and understanding (in addition to other factors) to inform engineering decisions.

Managing Complexity

System: A combination of components that work in synergy to collectively perform a useful objective

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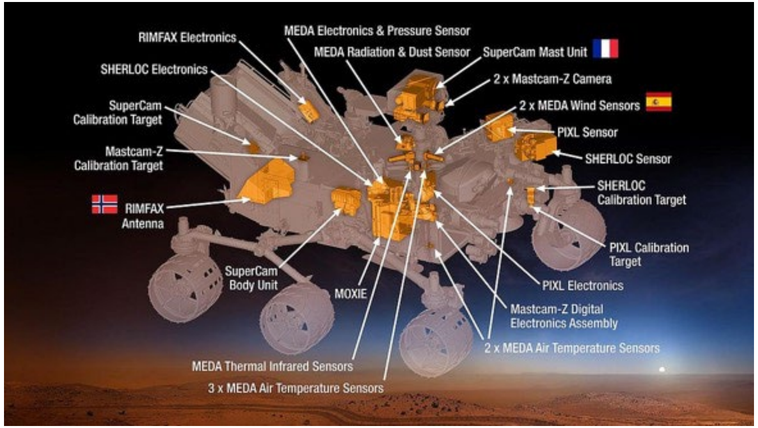
Systems Engineer

- Understands how each component effects the others (partial derivative of everything with respect to everything) and ensures that they work together to accomplish the (science) objectives
- Good listener and communicator
- Manages complexity and change – is the glue and the grease that holds the system together



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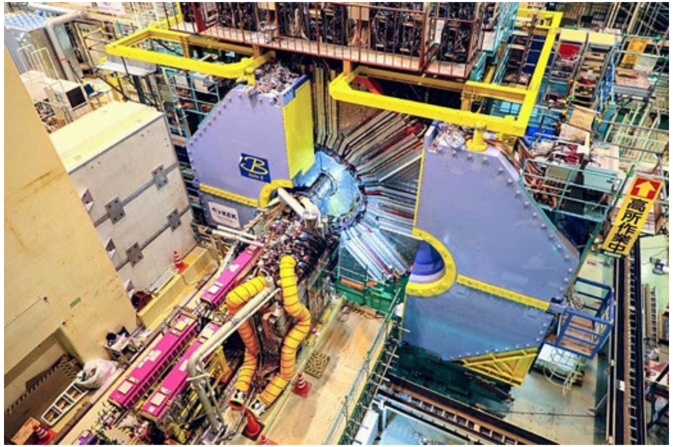
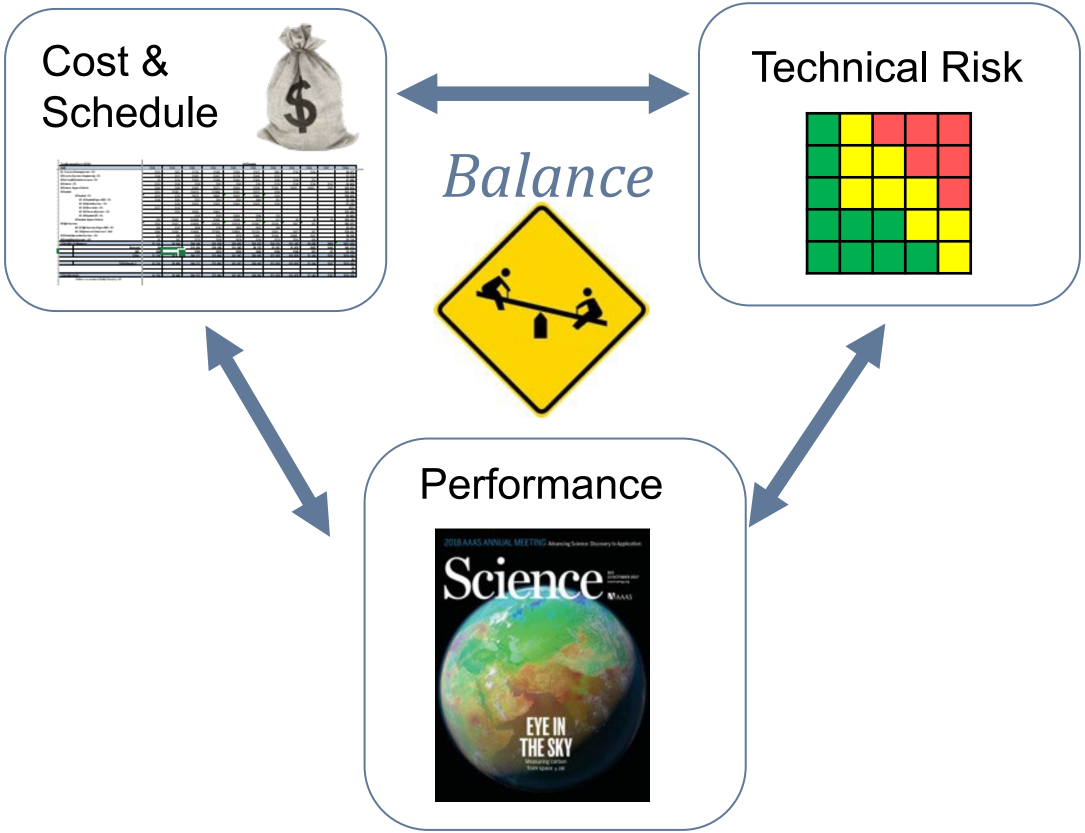


SuperKEKB accelerator and Belle II detector at the interaction region. Credit: Belle II/KEK

Seeking Balance



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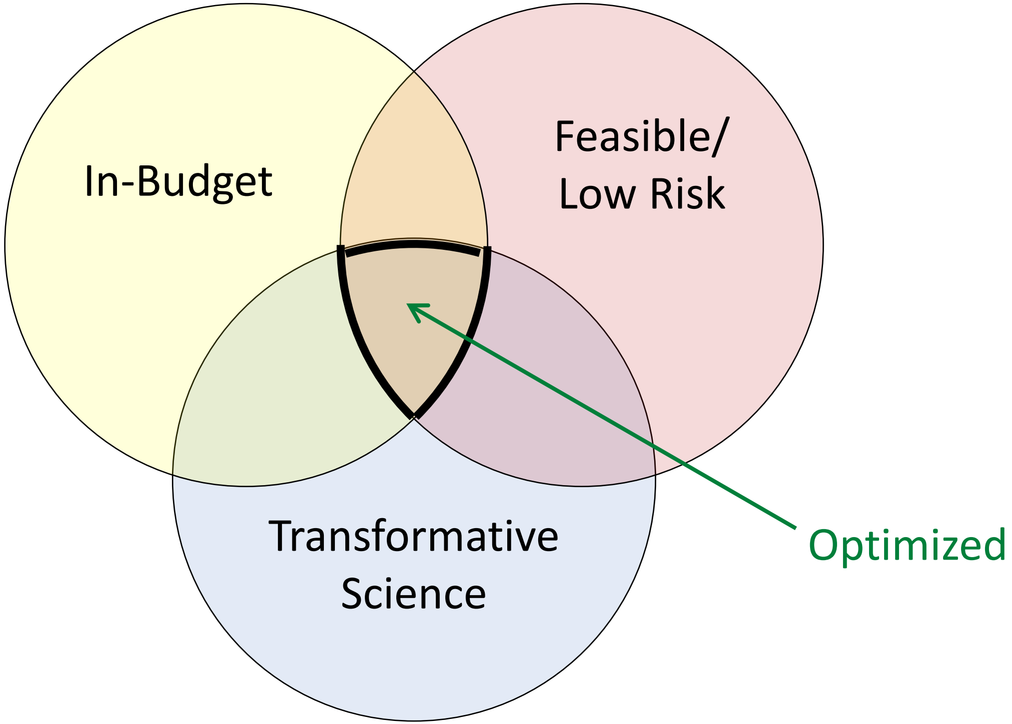
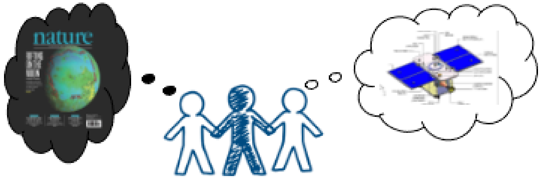


Architecting New Missions: Collaboration

Good architecture requires understanding both
user objectives and builder realities

Science



Engineering

Priorities,
Use scenarios

Capabilities,
Constraints

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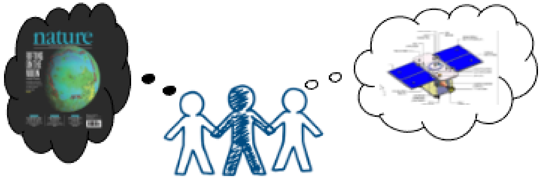
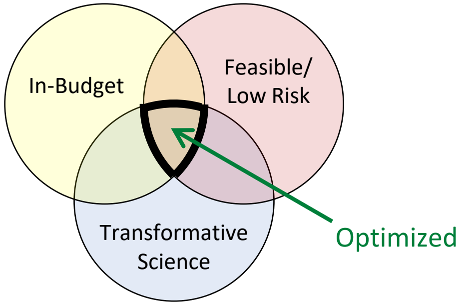


Engineering

✗ Science team defines architecture;
engineers receive instrument & mission requirements

✗ Engineers force science team
to immediately define and pursue
the “Minimum Science” option

✓SE and Science build mutual understanding,
and *collaborate* to balance science, risk, and cost



Architecting New Missions: Mapping the Landscape

Example from PICO mission concept study

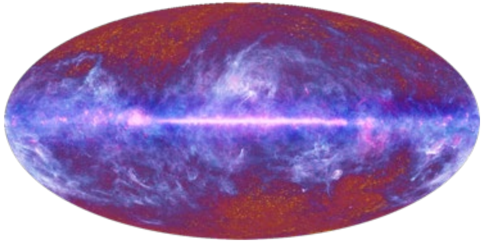
- Identify possible science objectives, and prioritize

Cosmological inflation (r, n_s)

Fundamental particles ($\sum m_\nu$, N_{eff})

Reionization (τ)

Galactic structure & dynamics (dust, magnetic fields)



- Identify important opportunities and challenges

Multiple new detector technology options enable great science, but require more development for space

Systematics / signal modulation / scan strategy

Telescope cooling and SubK focal plane cooling

- Research key resources and constraints

Mission budget ($)

Technology readiness deadline

Required risk mitigations (redundancy, …)

Compatible with potential launch vehicles

Architecting New Missions: Selecting an Architecture

Example from PICO mission concept study

- Identify key elements of the system
- Utilize parametric models and analogies for rough estimates of what is feasible
- Develop basic concept of operations

<u>Payload trade study</u>

Selected

(A) Imager only, or

1.4 m Imager

(B) Small Imager + Small Spectrometer, or

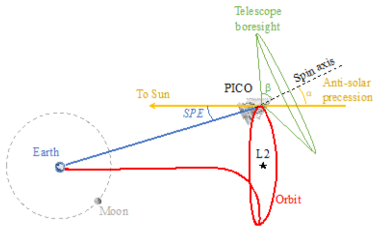
2x 20 cm Spectrometer + 50 cm Imager

(C) Spectrometer only

3x size of PIXIE

Similar to WMAP, *Planck*

Orbit Earth–Sun L2 Lagrange point;
Fixed-rate imaging while continuously spinning (1rpm) about a precessing axis (1/10hr)



Zero net angular momentum control architecture with heritage from SMAP mission

Defining Clear Quantitative Science Objectives

Example from SPHEREx mission

Science goal (broad *fundamental question* clearly tied to NASA goals)

Probe the origin of our universe

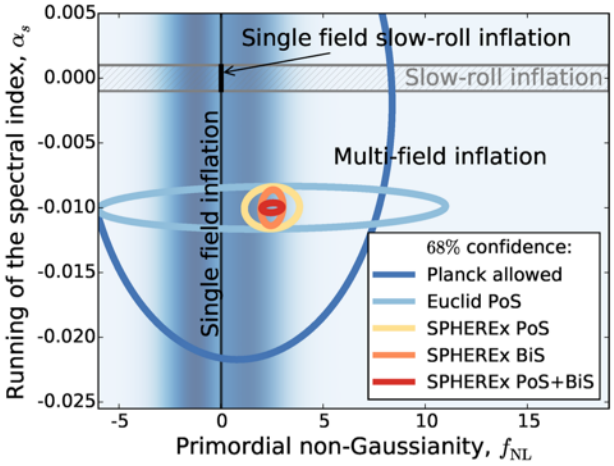
Specific *knowledge* (not data) milestone – well-posed question the mission answers

Discriminate between multi-field and single-field cosmological inflation models.

Science objective gives *quantitative* description of how (and how well) milestone is met

Test models of inflation by mapping the 3D distribution of galaxies to measure non-Gaussianity to a combined accuracy of $\Delta f_{NL} \leq 1$ (2σ) using both the power spectrum and the bispectrum

[multi-field models predict $|f_{NL}|>1$;
single-field predict $|f_{NL}|<0.01$]



Science Objectives Trace to Engineering Requirements

Example from SPHEREx mission

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Requirements		Mission Requirements
		Physical Parameters	Observables	Parameter	Requirement	
Probe the origin and destiny of our universe [NASA Science Plan]; Advance understanding of the fundamental physics of the universe [NWNH priority]	Test models of inflation by mapping the 3D distribution of galaxies to measure non-Gaussianity to a combined accuracy of $\Delta f_{NL} \leq 1$ (2σ) using both the power spectrum and the bispectrum (Fourier transforms of 2-point and 3-point galaxy correlation function, respectively)	Measure ≥7.5 million galaxy redshifts (a measure of galaxy distance) with accuracy $\sigma_z/(1+z) \leq 0.003$, to determine f_{NL} using the bispectrum to an accuracy $\Delta f_{NL} \leq 1.1$ (2σ). Measure ≥380 million galaxy redshifts with accuracy $\sigma_z/(1+z) \leq 0.1$ to determine f_{NL} using the power spectrum to an accuracy $\Delta f_{NL} \leq 2.3$ (2σ).	Galaxy spectral features, including emission bump at $\lambda \sim 1.6$ μm (in rest frame) are redshifted by (1+z). Template fitting enables determination of redshift (z).	*Wavelength range*, to support redshift determination for $0<z<1.5$	$0.8 \leq \lambda \leq 4$ μm	4 all-sky surveys each with ≥ 90 % voxel completeness for internal reliability Visit the same spot on the sky 6 months later to within 80″ (1σ) …
				Spectral resolving power, enabling redshift determination accuracy	$\lambda/\Delta\lambda$ >= 30	
				Point source sensitivity, to measure enough galaxy redshifts	$\Delta F_\nu \geq 18.4$ AB mag (5σ) at 2 μm [Fig. X]	
				Effective PSF, to control source blending	FWHM ≤ 8” at 0.75 μm	

- **Science-driven flow (left to right)**
- **Quantitative** (including uncertainty requirements on Science Measurements)

Science Models / Mission Simulators

Robust quantitative modelling enables (a) requirements development and (b) decisions with well understood impacts on science performance

Mission design & measurement schedule

L2 performance

Mission Science Model/Simulator

Non-flight software;
maybe Python/XLSX/Matlab…
e.g. NEOCam Survey Simulator

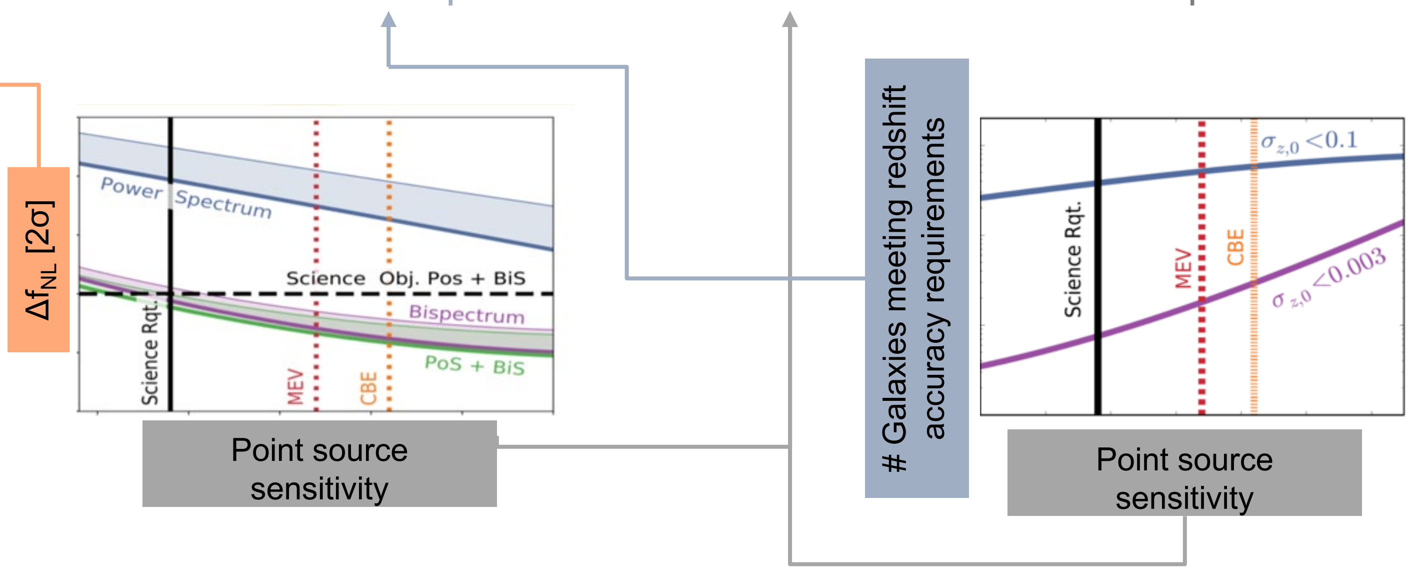
Simulated L1 performance

- Use during early formulation / architecture
  - A few big knobs to simulate different architectures across a broad design space
- Use during formulation mid-late formulation
  - More fine knobs to map trade space around baseline design
  - Allocate margins and set key performance requirements
  - Remember to validate (check) your models/simulator
- Continued use during mission development
  - E.g. margin tracking and trading, prioritization of limited resources, risk consequence rating, high-level V&V

Science Models / Mission Simulators

Example from SPHEREx mission

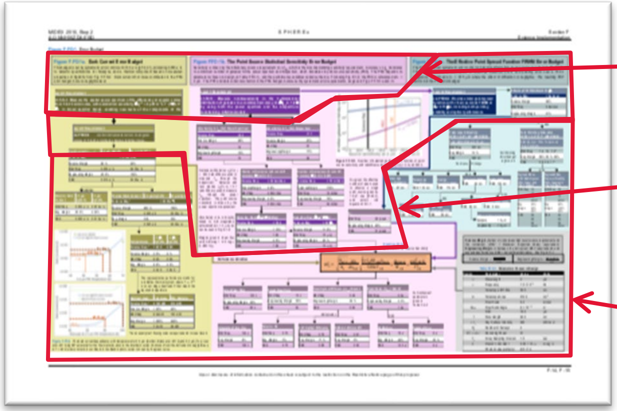
- Quantitatively map the relationships between the columns of your table, from Objectives → Measurement Requirements → Instrument & Mission Requirements



Performance Budgets

Example from SPHEREx mission

- Start with Level 1 requirements (derived from quantitative science objectives)
- Use science models to derive top-level engineering requirements (involve engineers in this)
- Trusted engineers can/should lead allocation from Level 2 to lower level requirements
- Include Observatory-level factors (not only instrument)
- Include contributions from nature / environment
- Consider systematic (not only statistical) error sources

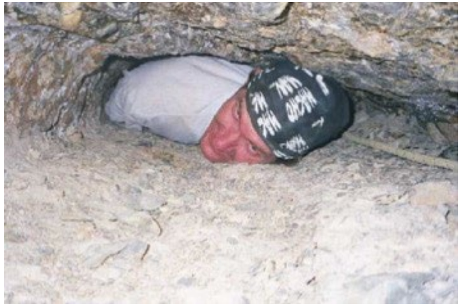


Science reqts (L1)
(e.g. Δf_{NL})

Top-level engineering reqts (L2)
(e.g. sensitivity, PSF)

Important lower level
engineering reqts (L3,L4)
(e.g. optical efficiency)

Margin



Source: Reddit.com

- Margin = Difference between what is required and what is expected
- Provides maneuvering room to adapt to new information / challenges
- Margin is needed on resources (e.g. mass, power) and
  on performance (e.g. sensitivity, PSF)
- Margin is needed at multiple levels in the organizational structure
  - Subsystem margin
  - Project margin
  - Science margin
- Margin expectations scale with uncertainty and criticality
  - For some standard parameters (e.g. mass),
    JPL Design Principles establish minimum margins

Summary

Collaborative fusion of science, technology, and systems engineering, with clearly defined science objectives and robust quantitative modelling, supports formulation of optimized scientifically-transformative projects.

Thank you for your time, and shared ideas.

Jet Propulsion Laboratory
California Institute of Technology