How to link science to architecture/trades and classify investigations as precursor, preparatory, follow-up, or other science

John K. Ziemer
Program Manager, Strategic Missions and Technology
JPL Astronomy and Space Physics Formulation Office

Significant Contributions from:
Kelley Case, Alfred Nash, and Randii Wessen
JPL Innovation Foundry
https://jplfoundry.jpl.nasa.gov

Large Mission Study Team
NASA Science Mission Directorate

This document has been reviewed and determined not to contain export controlled technical data.
California Institute of Technology © 2022. All rights reserved.
Precursor Science

Science investigations that will inform mission architectures and trades with the goal of reducing mission design and development cost, scope, and risk where possible.

Enabling and Realizing Large Strategic Missions

Great Observatories Mission and Technology Maturation Program

- Infrared/optical/UV mission
- High resolution X-ray imaging mission
- Far-IR imaging and spectroscopy mission

2022
Review
2032
Implement Infrared/optical/UV mission

Taken from 2020 Astrophysics Decadal Survey (Ref. [1])
Science Traceability: Going from Goals to Requirements

<table>
<thead>
<tr>
<th>Goals</th>
<th>Questions</th>
<th>Objectives</th>
<th>Observables</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>These come from NASA and the Decadal Survey, often verbatim and always at a high level</td>
<td>These come from science communities (i.e. ExEP Science Gap List) and help focus the science investigation</td>
<td>A concrete statement of what the science investigation will achieve and/or the hypotheses to be tested</td>
<td>The physical quantities and parameters that need to be observed (i.e. spectral lines, feature sizes, etc.)</td>
<td>What actually will be measured or detected, including any precision or accuracy requirements</td>
</tr>
</tbody>
</table>

- As we go from left to right, the details of **and the rationale for** the investigation are captured; we move from goals to requirements, causes to effects, and we provide focus.
- Each progression requires models of the science (both expected conditions and behavior), experiment/measurement, and observatory/instrument performance.
- We cannot skip any step – we must know the rationale as part of developing the requirements to effectively design the investigation and observatory.
Science Traceability: Going from Goals to Requirements

- The precursor science work will help move from left to right in this flow by providing not just the desired requirements and priorities, but the rationale for them and the “partials”
- It’s critical to have science participation in the iterative process of understanding the science drivers and then looking for a feasible, and eventually optimal, implementation
- In the end, the science objectives for the next Great Observatories will be developed with participation by the community, and there is a lot of great work to do!
Early Concept Challenges
The Concept Maturity Levels (CMLs) were developed to help guide concept teams through formulation progression, before Phase A to the Preliminary Design Review (PDR).

NASA agrees to cost and scope at Key Decision Point (KDP)-C, right after PDR, but there are many steps along the way – even in pre-pre-Phase A!

Pre-Phase A ends at KPD-A; A goal might be to reach CML 5 by the review recommended by Decadal Survey.
Concept Space

Research  Guide  Create  Question  Explore  Stretch  Narrate  Test  Discover  Evaluate  Reveal  Materialize
The Six Dimensions of Concept Maturity

- Using CMLs helps concept teams understand the work that needs to be done in parallel during pre-Phase A
  - The Large Mission Study Report recommended using CMLs and SMD is studying how they can be incorporated into NASA’s practices
- Each of the six dimensions of concept maturity has its own set of expected status and evidence at each CML
- If any one dimension gets ahead or is not connected to the others, ideas and requirements can become “locked in” too early
Exploring the Trade Space Through CMLs

- Prior to Phase A (CML 1 - 4)
  - Requirement analyses and architecture trades will be conducted to quantify science in comparison to cost (clearly identifying mission requirements)
  - Descope options will be developed and documented during Pre-Phase A and evaluated at KDP-A to determine realism and feasibility of options
  - Program Office will ensure that independent assessments of architecture trades and descope options are conducted

- At KDP-A (CML 5)
  - Pre-Phase A architecture trades and descope options will be evaluated at KDP-A for assessment of mission concept maturity, technology maturity, risks, cost and schedule realism, and project maturity, to enable the making of early decisions and programmatic adjustments
How Are Trades Explored and Decisions Made?

• Many, many different ways of reaching each CML (making decisions)
• My “Top 10” keys to success / best practices:
  • A well connected, diverse team of experts, across all 6 CML dimensions
  • Experienced leadership and inclusive mentorship with intentional feedback
  • A well defined, open process (i.e. criteria) that is communicated early-on
  • Stay focused on sharing, use the best tools for team access to latest data
  • Allow multiple cycles of prototyping ideas: create / test / learn / teach
  • Scrutinize ideas, not people – respectful questioning and active listening
  • Keep it at the right level: start high, dive deep, then come back up again
  • Set deadlines and don’t let any dimension of the concept get too far behind
  • Understand risks and uncertainties – be honest and quantitative
  • Document the outcome and rationale outward to build consensus
Some Notes on Early CMLs

• It includes both expanding and contracting, building off of what has been done before, but allowing for new advancements and ideas
  • We are definitely in the expansive phase, but not unconstrained
• We start with the science, but all parts of the concept need to mature together in parallel
  • Resist jumping to a point design or baseline too early – very challenging!
  • Understand the driving parameters and sensitivities in the design, which requires system models of the science, observatory, data processing, etc.
• It is an iterative process – get ideas out there early and test them
  • To enable discovery, we need to know our desires, capabilities and constraints
  • Using prototype ideas early helps us find the relations between science, engineering, and cost along with what models we need to evaluate options
# Recommendations from the SMD Large Mission Study

## Classification of Recommendations from the Large Missions Study

<table>
<thead>
<tr>
<th>No.</th>
<th>Recommendation Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pre-Phase A Team Composition</td>
</tr>
<tr>
<td>2</td>
<td>Pre-Phase A Architecture Trades and Descope Options</td>
</tr>
<tr>
<td>3</td>
<td>System Maturity Assessment</td>
</tr>
<tr>
<td>4</td>
<td>Technology Integration into Complex Systems</td>
</tr>
<tr>
<td>5</td>
<td>Analytical Tools</td>
</tr>
<tr>
<td>6</td>
<td>Cost and Schedule Estimation</td>
</tr>
<tr>
<td>7</td>
<td>Standing Review Boards (SRBs)</td>
</tr>
<tr>
<td>8</td>
<td>Instrument Selection Process</td>
</tr>
<tr>
<td>9</td>
<td>SMD Capabilities</td>
</tr>
<tr>
<td>10</td>
<td>Center Capabilities</td>
</tr>
</tbody>
</table>

![Classification of Recommendations from the Large Missions Study](image)

Taken from SMD “Large Mission Study Report” presentation, see Ref. [6] and [link](link).
## Bottom Line Up Front – SMD Large Missions Study Implementation Plan

<table>
<thead>
<tr>
<th>No.</th>
<th>Large Missions Study Recommendation</th>
<th>Disposition</th>
<th>Large Missions Study Implementation Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pre-Phase A Team Composition</td>
<td>Accept</td>
<td>Staffing will be based on needed skill sets and expertise (not based on availability of personnel). An Agency-wide search shall be conducted, followed by a nationwide search, if needed.</td>
</tr>
<tr>
<td>2</td>
<td>Pre-Phase A Architecture Trades and Descope Options</td>
<td>Accept</td>
<td>Program Office will conduct independent assessment of Pre-Phase A architecture trades and descope options for evaluation at KDP-A. Implementation effective immediately.</td>
</tr>
<tr>
<td>3</td>
<td>System Maturity Assessment</td>
<td>Accept w/Follow-Up</td>
<td>Further action is required. A team, sponsored by the SMD DAA/P and led by the SMD Chief Engineer, will be formed for further investigation.</td>
</tr>
<tr>
<td>4</td>
<td>Technology Integration into Complex Systems</td>
<td>Partially Accept</td>
<td>Mandate increased scrutiny of technology maturity at reviews and KDPs. Implementation effective immediately. Further action is required - A strategic approach will be developed by the SMD Chief Technologist to identify technology needs and funding sources for technology development.</td>
</tr>
<tr>
<td>5</td>
<td>Analytical Tools</td>
<td>Partially Accept</td>
<td>Large strategic missions will incorporate common tool sets, when possible, and establish an agreed margin and risk philosophy with partners and providers early in the life cycle.</td>
</tr>
<tr>
<td>6</td>
<td>Cost and Schedule Estimation</td>
<td>Accept</td>
<td>Life cycle cost estimates shall be communicated in terms of bins for Pre-Phase A and ranges for Phases A and B to set external expectations. Implementation effective immediately.</td>
</tr>
<tr>
<td>7</td>
<td>Standing Review Boards (SRBs)</td>
<td>Accept</td>
<td>The SMD policy of convening the SRBs prior to MCR, and when required, convening of the Independent Review Boards (IRBs), has already been implemented. Initiating SRB kickoff meetings.</td>
</tr>
<tr>
<td>8</td>
<td>Instrument Selection Process</td>
<td>Partially Accept w/Follow-Up</td>
<td>Further action is required. A team led by the SMD Deputy AA for Research will be established. Modification of SMD policy may be required.</td>
</tr>
<tr>
<td>9</td>
<td>SMD Capabilities</td>
<td>Accept</td>
<td>Program Offices of large missions will be adequately staffed early in pre-formulation in order to perform programmatic assessments and oversight. Implementation effective immediately.</td>
</tr>
<tr>
<td>10</td>
<td>Center Capabilities</td>
<td>Accept</td>
<td>SMD and Centers have ownership and accountability of large strategic missions and will work closely to identify and solve problems. Implementation effective immediately.</td>
</tr>
</tbody>
</table>

The SMD Large Missions Implementation Plan will require an intentional shift in how we approach the development of our missions.
Science in Early CMLs

For the best exploration of the trade space, science driven investigations address a specific question with testable hypotheses / predictions

- They provide the rationale and help us derive science-driven requirements
- We may not be able to completely answer the question or address all the hypothesis due to other constraints, but we can get a sense of science return vs. capability (usually model based)

Science investigations based purely on measurement capability can be open ended, but hard for the rest of the concept team to derive requirements

- We need to be able to have “discovery space”, but when are we good enough?
- Pushes the capability to the limit of what’s feasible (often hard to know!)

Developing early CML science cases is an iterative process, balancing our ambitions to discover and explore the universe within the reality of limited capabilities and resources
Precursor Science: Feasibility or “Must Haves”

- At CML 2, we look for feasibility: the thresholds in ALL six concept dimensions that make a mission architecture acceptable (or not)
- For science, we must improve and expand our knowledge and understanding – but how far do we stretch ourselves?
- Use both hypothesis tests to determine minimum requirements and how far we need to improve on existing capability in our discovery space
- Often times, science feasibility can be shown as an “undiscovered country” plot, providing the requirement and rationale in one graphic

Science investigations that will inform mission architectures and trades with the goal of reducing mission design and development cost, scope, and risk where possible.
Examples of “Undiscovered Country” Plots for CML 2

**FIGURE 2.5** The population of known exoplanets in 2010 (top) and 2020 (bottom). Each symbol represents a known extrasolar planet, colored by initial discovery method. Hollow symbols are planets that have been discovered. Filled symbols are planets whose atmospheric composition have been characterized by measurements of its spectrum or brightness. Over the past decade astronomers have begun to move from the era of planetary census-taking to detailed characterization, and the next decades will both complete the missing parts of the census—planets like our own solar system—and see an explosion in characterization. SOURCE: D. Savransky and B. Macintosh, with data from the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

The radial velocity and transit methods are best suited for finding planets on relatively close-in orbits. A method prioritized by New Worlds, New Horizons, gravitational microlensing, will be used by the Roman Space Telescope in this decade to complete the planetary census by finding planets from 1 to 100 AU, and even free-floating planets. Microlensing exploits the bending of light by the gravity of the

---

Image Credit: NASA/JPL/Caltech

**Figure 3:** Contrast (ratio of planet brightness to host star brightness) versus apparent angular separation. The filled orange circles indicate the direct imaging of young, self-luminous planets imaged in the near-infrared by ground-based telescopes. Contrasts for the planets of the Solar System are for analogous planets placed 10 pc away. The solid black dots are contrast estimates of measured radial velocity planets, including Proxima Cen b. The orange curves show measured performance of ground-based coronagraphs. The GPI curve shows typical performance, while the SPHERE curve shows the best achieved performance to-date on Sirius. Achieved performance with HST/ACS coronagraphic masks, and the predicted performance of JWST/NIRCam masks are also shown. The predicted and required performance at 565 nm for the WFIRST coronagraph instrument (CGI) is shown as solid black curves. The “predicted” curves extending from 0.13” to 0.4” is based on performance achieved in a testbed. From 0.4” to 1”, performance is based on a coronagraph mask designed to maximize outer working angle. For consistency, the planets discovered in the near-infrared are shown with vertical arrows pointing to the predicted contrast ratios at visible wavelengths (WFIRST-CGI is expected to conduct science between 442 and 980 nm).
Examples of “Undiscovered Country” Plots for CML 2

FIGURE J.4 FIR to X-ray spectral energy distribution for a black hole seed at $z = 9$. The Origins sensitivity curve is the thick red line with arrows on the upper left, the Lynx sensitivity curve is the thick green line on the lower right. Lynx detects all stages of black hole growth from 5 Myrs (thin, solid red line) after accretion begins, while Origins detects the later stages ($> 75$ Myr, thin green line). The Origins OSS sensitivity plotted is binned to a resolving power (RP) of 3. The [OIV] 25.9 um line is detectable by Origins at the native resolving power of 300 and is an important diagnostic of black hole mass and accretion rates. SOURCE: Adapted from F. Pacucci et al., 2019, Detecting the birth of supermassive black holes formed from heavy seeds, Bulletin of the AAS, 51(3). Retrieved from https://baas.aas.org/pub/2020n3i117. Reproduced with permission.

Taken from 2020 Decadal Survey Report, see Ref. [1]
Examples of “Undiscovered Country” Plots for CML 2

From First Light to Life

complement to tracer molecules such as carbon monoxide (CO), which rely on an uncertain calibration and are only visible along sightlines with high column density (typically, $A_v > 1$). Indeed, Herschel observations by Pineda et al. (2017) have demonstrated that up to half the molecular gas in the Milky Way may be in a “CO-dark” phase and invisible to traditional mm-wave surveys.

Meanwhile, small dust grains are measured via broad emission bands from Polycyclic Aromatic Hydrocarbons (PAHs), that are stochastically heated by individual photons and subsequently emit a distinct pattern of broad features in the infrared (3-20 µm). Larger grains are detected via emission and absorption bands from silicate dust and far-infrared continuum emission from grains in thermal equilibrium with their environments (Table 1-1).

The PAH features indicate redshift, UV flux (and hence star formation rate), and the presence of an AGN, which destroys them. The temperature and luminosity of the larger grains is related to the star formation rate.

The important lines and dust features lie in a large wavelength gap between JWST and ALMA, which Origins fills (Figure 1-2).

Figure 1-1: (Above) Origins measures the redshifts, star formation rates, black hole accretion rates, and metal and dust content in galaxies. The infrared spectrum of the nearby active galaxy, Circinus (see inset), is shown using Infrared Space Observatory data (Moorwood, 1999). Emission lines from highly ionized gas heated by the central active nucleus are marked in red, those coming from gas heated by young stars are marked in blue, and those from warm molecular gas are marked in green. PAH molecules are excited by UV photons, and emit broad features in the mid-infrared, through bending and stretching modes.

Figure 1-2: (Right column) The spectral reach of Origins over cosmic time. Schematic representation of how the key spectral diagnostic features of AGN (red), star formation (blue), and energetic feedback (green) move through the wide bandpass of the Origins Survey Spectrometer (OSS) with look-back time. Origins can measure all of these important processes over the entire history of galaxy evolution, filling in a key gap in wavelength and discovery space between JWST and ALMA.

Taken from Origins Concept Study Report, see Ref. [7]
Precursor Science: Science Return Gradient or “Wants”

*Science investigations that will inform mission architectures and trades with the goal of reducing mission design and development cost, scope, and risk where possible.*

- At CML 3, we look for the *partials* or gradient of the quality of the science returned by the mission vs. some measurement parameter (i.e. bandwidth, resolution, etc.); *attempting to quantify this return is key*
- For science, we would always like to have better and more capability – but how does the science return really depend on the measurements?
- We can build off the “must haves” as a threshold or minimum science return, and then quantify the advantage of having even more capability
- This is often model based, but we need to quantify input and output uncertainties along with parameter sensitivities to be most useful
The Science Return Diagram

- Often challenging for science teams to determine exact requirements, but easier to come to more of a consensus on how the science improves vs. “X” parameter
- One tool that can help is to “diagram” one science question and evaluate the quality of return into four distinct levels
- For each candidate science question, determine the observables and then look for key measurement parameters that have the biggest impact on science return
  - Look for thresholds and cliffs – the partials
  - Provide rationale for each level

**Science Return Diagram**

<table>
<thead>
<tr>
<th>NASA Goal:</th>
<th>Science Question:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science Objective: (hypothesis or discovery)</td>
<td></td>
</tr>
<tr>
<td>Hypothesis Tests, Predictions, or Models</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Observables</th>
<th>Critical Scales</th>
</tr>
</thead>
<tbody>
<tr>
<td>If this, then that…or, To discover “X”, we need this…</td>
<td>Key features and physical parameters</td>
<td>Spatial, temporal, spectral, etc.</td>
</tr>
</tbody>
</table>

**Experiment Characteristics (quantitative narratives)**

<table>
<thead>
<tr>
<th>Science Return</th>
<th>Observables</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>State-of-the-Art (SOA): what is already known or observed? (Include projections for any mission past PDR); What are the key parameters for the mission?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enhancing: Take one observable / measurement (i.e. bandwidth, resolution, etc.) from the SOA and improve it - how much to make a new impact (answer some part of the science question)?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enabling: Beyond enhancing, allowing most, but not all, of the science question to be addressed with significant progress in advancing the field. (note: can have multiple options)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breakthrough: Addresses entire science question and / or distinguishes between all relevant hypothesis; recognized community wide as a significant advancement in the field.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Science Return Diagram Example – Psyche Mission

- Example from early-on in the Psyche Mission formulation
- Note that the “water lines” were drawn later, after the engineering teams assessed the challenges associated with each level, while the science team converged on the baseline and threshold science requirements
- The science return levels can be distinguished by precision, accuracy, range, resolution, coverage, # of targets, etc. but each needs to have a description of what different science will be returned

<table>
<thead>
<tr>
<th>Science Return Level</th>
<th>Mission</th>
<th>Spatial Scale</th>
<th>Temporal Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>State of the Art</td>
<td>Dawn</td>
<td>35 m/pixel</td>
<td>5.5 hours (LAMO)</td>
</tr>
<tr>
<td>Enhancing</td>
<td>Dawn s/c at new class of asteroid</td>
<td>35 m/pixel</td>
<td>5.5 hours (LAMO)</td>
</tr>
<tr>
<td>Enabling</td>
<td>Add a magnetometer &amp; laser altimeter</td>
<td>35 m/pixel</td>
<td>5.5 hours (LAMO)</td>
</tr>
<tr>
<td>Breakthrough</td>
<td>Land on surface and return a sample</td>
<td>450 microns/pixel</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

Taken from Ref. 5; LAMO = Low-altitude mapping orbit
Examples of Science Return Plots for CML 3

**FIGURE 7.6** Potentially habitable exoplanet yield vs telescope diameter for different telescope architectures. Right axis shows the number of habitable zones surveyed (weighted by completeness); left axis shows the expected number of planets discovered assuming the occurrence rate of rocky planets in the optimistic habitable zones of different stars, eta_earth=0.24 (Bryson et al. 2021). The red dot shows the expected yield for the target 6-m inscribed diameter. NOTE: Habitable zone is defined as 0.95-1.67 AU for planets of 0.8-1.4 Earth radii. SOURCE: Adapted from C. Stark (Space Telescope Science Institute), D. Mawet (California Institute of Technology), and B. Macintosh (Stanford University).

**FIGURE I.1** Simulated UV-NIR exoearth spectrum that highlights absorption from several key molecules for biosignature detection such as ozone, molecular oxygen, water, and carbon dioxide. SOURCE: LUVOIR and HabEx final reports. Courtesy of J. Lustig-Yaeger (University of Washington).

Taken from 2020 Decadal Survey Report, see Ref. [1]
Examples of Science Return Plots for CML 3

**Key Capabilities**

- Map CGM in emission to 0.5 kpc; PSF < 1", $A_E = 2$ m².
- Probe CGM in absorption at $\lambda > 4,000$ cm$^{-2}$ and $\lambda/\Delta \lambda > 5,000$.
- Map velocities in ~100 km s$^{-1}$ galactic outflows: microcalorimeter with $E/\Delta E = 2,000$ at $E = 0.6$ keV.
- Study AGN feedback in galaxies and clusters: microcalorimeter with 0.5" pixels.

---

**Fig. 3.3**—The impact of X-ray spectral resolution on the ability to deduce coronal structures and the contribution from each member of a binary. Discriminants between various scenarios, such as those described in the leftmost column of text, are found only when the X-ray spectral resolution is sufficiently high. The panels, adapted from Fig. 10 of Hussain et al. [273], illustrate this effect for the case of the nearby binary YY Cen. The panels are arranged on a logarithmic axis of spectral resolution ($R = \lambda/\Delta \lambda$) that increases toward the left. Only the exquisite spectral resolution delivered by the Lynx X-ray Grating Spectrometer, with a goal of $R = 7,500$, will enable us to clearly distinguish between these scenarios. *Chandra* and *Athena* are entirely unable to do so.

*Taken from Lynx Concept Study Report, see Ref. [7]*
Examples of Science Return Plots for CML 3

Figure ES-7: Origins’ key science program requires a cold telescope with a primary aperture diameter of 5.3 m. This requirement comes primarily from the exoplanet science case to detect biosignatures in a 5-year mission, given that transit durations are fixed and sensitivity cannot be recovered with a longer single-epoch integration, unlike most other proposed Origins observations. The extragalactic study places an aperture size requirement of >5 m, based on the need to detect a statistically significant sample of galaxies at z > 6, to study the formation mechanisms and physical properties of dust and metals during reionization. The minimum primary aperture diameter is 3 m to enable an effective extragalactic and Galactic science program, where source confusion does not compromise the telescope’s ability to conduct spectroscopic studies of galaxies at z = 2–3 and the sensitivity is not too poor to study water and gas in proto-planetary disks at the distance of Orion.

Taken from Origins Concept Study Report, see Ref. [7]

Figure 1-5: Diagnostic power of IR fine-structure lines for identifying and quantifying AGN. Traditional optical diagnostic line ratios can fail to detect highly obscured AGN. Here, buried AGN (red squares) are identified in a sample of nearby (D < 15 Mpc) galaxies via their mid-IR diagnostic lines with Spitzer IR spectroscopy (left) when optical diagnostics (right) suggest star forming or composite sources. The [NeV]/[NeII] and [OIV]/[NeII] (not shown) MIR line ratios are excellent measures of the AGN contribution, and the high ionization line luminosities can be used to estimate the black hole accretion rates. Figures adapted from Goulding & Alexander (2009).

Taken from Origins Concept Study Report, see Ref. [7]
One Trade Space Exploration / Decision Making Method for Complex, High-Value Problems: Kepner-Tregoe Matrix

- This is a process that has been used by NASA Astrophysics Division to look at high-level trades and make decisions
- Start with a decision statement, then determine the criteria and describe the options, then perform the evaluation (can be technical in nature), and finally identify risks and opportunities for each option
- You have the opportunity to contribute to the science Musts, Wants, and Risks through the precursor science call!

The Kepner-Tregoe Methods and associated decision matrix were developed by the Rand Corporation in the 1950’s; see “The Rational Manager” by Kepner and Tregoe in 1965; See Ref [8].

For more details, see recent “Choosing the Future: The Kepner-Tregoe Matrix for Complex Trades” presentation and recording by Gary Blackwood (See Ref. [9]) at https://exoplanets.nasa.gov/exep/technology/tech_colloquium/
Precursor vs. Preparatory or Follow-up Science

To Summarize:

• **Precursor Science** informs the mission architecture and trades, which we need to start soon, so it’s part of the next stage of the Great Observatory Maturation Program’s “Analysis of Alternatives”
  
  • We need your help with this work now, looking for natural gaps, thresholds, and gradients in the science return vs. measurement parameters

• **Preparatory Science** informs data / interpretation or early operations; potentially from new observations, but needed just before or even after launch to help inform the best way to conduct investigation

• **Follow-up Science** provides additional data and investigations that follow up on discoveries or other science from the mission; occurs after launch or potentially with coordination / planning prior to launch
Acronyms

• AO Announcement of Opportunity
• APD Astrophysics Division
• CML Concept Maturity Level
• CSR Concept Study Report
• KDP Key Decision Point
• MCR Mission Concept Review
• MDR Mission Definition Review
• PDR Preliminary Design Review
• SMD Science Mission Directorate
• SRR System Requirements Review
References


Backup Charts
# NASA Flight Project Life Cycle

**FIGURE 3.0-1 NASA Space Flight Project Life Cycle from NPR 7120.5E**

Taken from NASA Systems Engineering Handbook, [https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf](https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf)
Mission Life Cycle Cost vs. Time

Cumulative Percentage Life Cycle Cost against Time

- 8% Concept
- 15% Design
- 20% Develop
- 50% Prod/Test
- 100% Operations through Disposal

Cost to Change Design Direction: 3-6x

- MCR Mission Concept Review
- SRR System Requirements Review
- SDR System Definition Review
- PDR Preliminary Design Review
- CDR Critical Design Review
- SIR System Integration Review
- ORR Operational Readiness Review
- DR/DRR Decommissioning/Disposal Readiness Review

Adapted from INCOSE-TP-2003-002-04, 2015