The Science Traceability Matrix

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Overview of the Science Traceability Matrix

- The STM is a required NASA proposal element that shows how science goals and objectives “trace” (flow down) to instrument and mission requirements
- The STM serves as the backbone of the Science and Science Implementation sections
- It is pivotal to proposal success because it answers the questions:
  - Does the science address NASA goals?
  - Does the investigation address the science?
  - Does the instrument/mission implement the investigation robustly?

Why are STMs so important?

- A compelling STM is critical to proposal success
  - Proposals live or die based on how well the STM is crafted *and* explained
  - A strong STM reflects a strong science team, strong systems engineering team, and solid fundamental concept
- STMs require <u>three different models</u> for each investigation to flow up and down between column groupings:
  - Science Model
  - Measurement/Experiment Model
  - Instrument Performance Model
- Each model must be developed and explained well in the proposal—*this is hard!* If Review Boards do not have visibility into the STM and can't <u>independently verify performance claims</u>, you are likely to get major science and/or science implementation weaknesses
- Even experienced PIs and proposal teams are likely to struggle with the STM—especially if any new measurement techniques are being proposed
- ***As a result, Principal Investigators must pay a lot of attention to this topic***

Standard AO Requirement for the STM

- “Traceability from science objectives to measurement requirements to instrument performance requirements, and to top-level mission requirements shall be provided in tabular form and supported by narrative discussion. Projected instrument performance shall be compared to instrument performance requirements.”
  - “The Science Traceability Matrix provides the reference points and tools needed to track overall mission requirements, provide systems engineers with fundamental requirements needed to design the mission, show clearly the effects of any descoping or losses of elements, and facilitate identification of any resulting degradation to the science.”

Standard STM Format

Column #	1	2	3	4	5	6	7	8
	Science Goals	Science Objectives	Scientific Measurement Requirements Observables	Physical parameters	Instrument Performance Requirements		Projected Instrument Performance	Mission Requirements (Top Level)
	Goal 1 Goal 2		Absorption line Emission line	Column density of absorber Density and temperature of emitter	Alt. Range	XX km	ZZ km	Observing strategies: requires yaw and elevation maneuvers Launch window: to meet nadir and limb overlap requirement. Window applies day to day
	Etc.	Objective 1		Size of features	Vert. Resol.	XX km	ZZ km	Need AA seasons to trace evolution of phenomena
			Morphological feature		Horiz. Resol.	XX deg x XX lat x XX long	ZZ deg x ZZ lat x ZZ long	
				Rise time of eruptive phenomenon	Temp. Resol.	XX min	ZZ min.	Need AA months of observation to observe variability of phenomena
					Precision	XX K	ZZ K	
			Rate of change of observable phenomenon		Accuracy	XX K	ZZ K	
		Objective 2 to N			Repeat above categories			

STM Flows Down from Goals to Objectives to Requirements

Science Goals	Science Objectives	Scientific Measurement Requirements: Observables	Scientific Measurement Requirements: Physical parameters	Instrument Performance Requirements		Projected Instrument Performance	Mission Requirements (Top Level)
Goal 1	Objective 1	Absorption line	Column density of absorber	Alt. Range	XX km	ZZ km	Observing strategies: requires yaw and elevation maneuvers
Goal 2		Emission line	Density and temperature of emitter				Launch window: to meet nadir and limb overlap requirement. Window applies day to day
Etc.			Size of features	Vert. Resol.	XX km	ZZ km	Need AA seasons to trace evolution of phenomena
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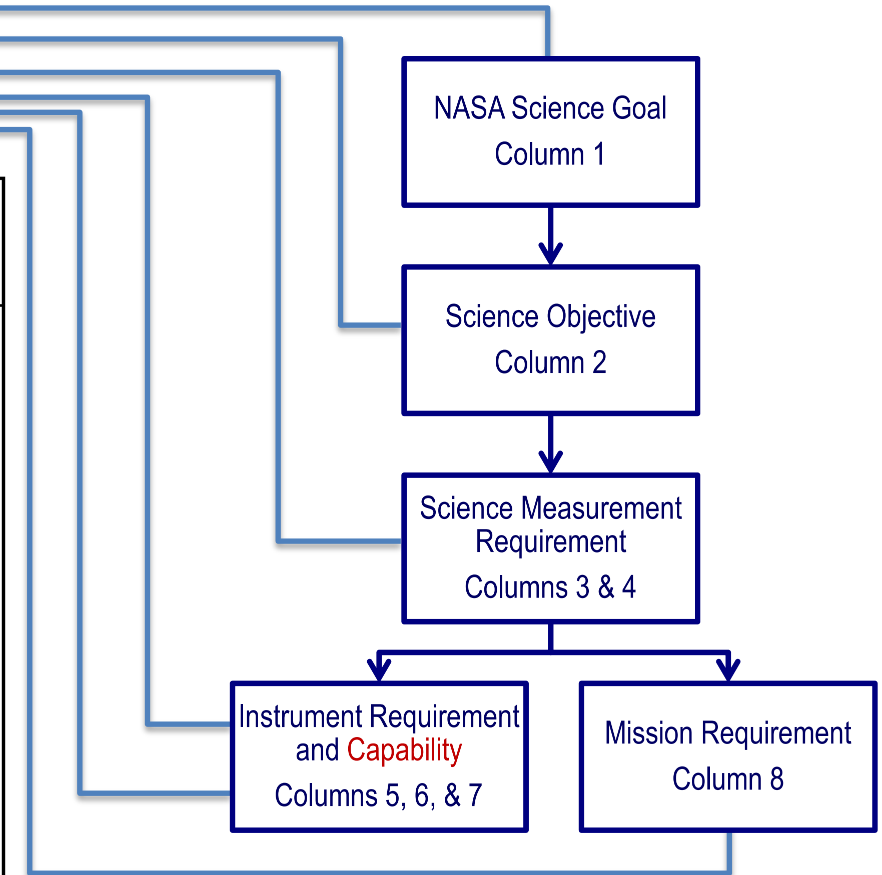
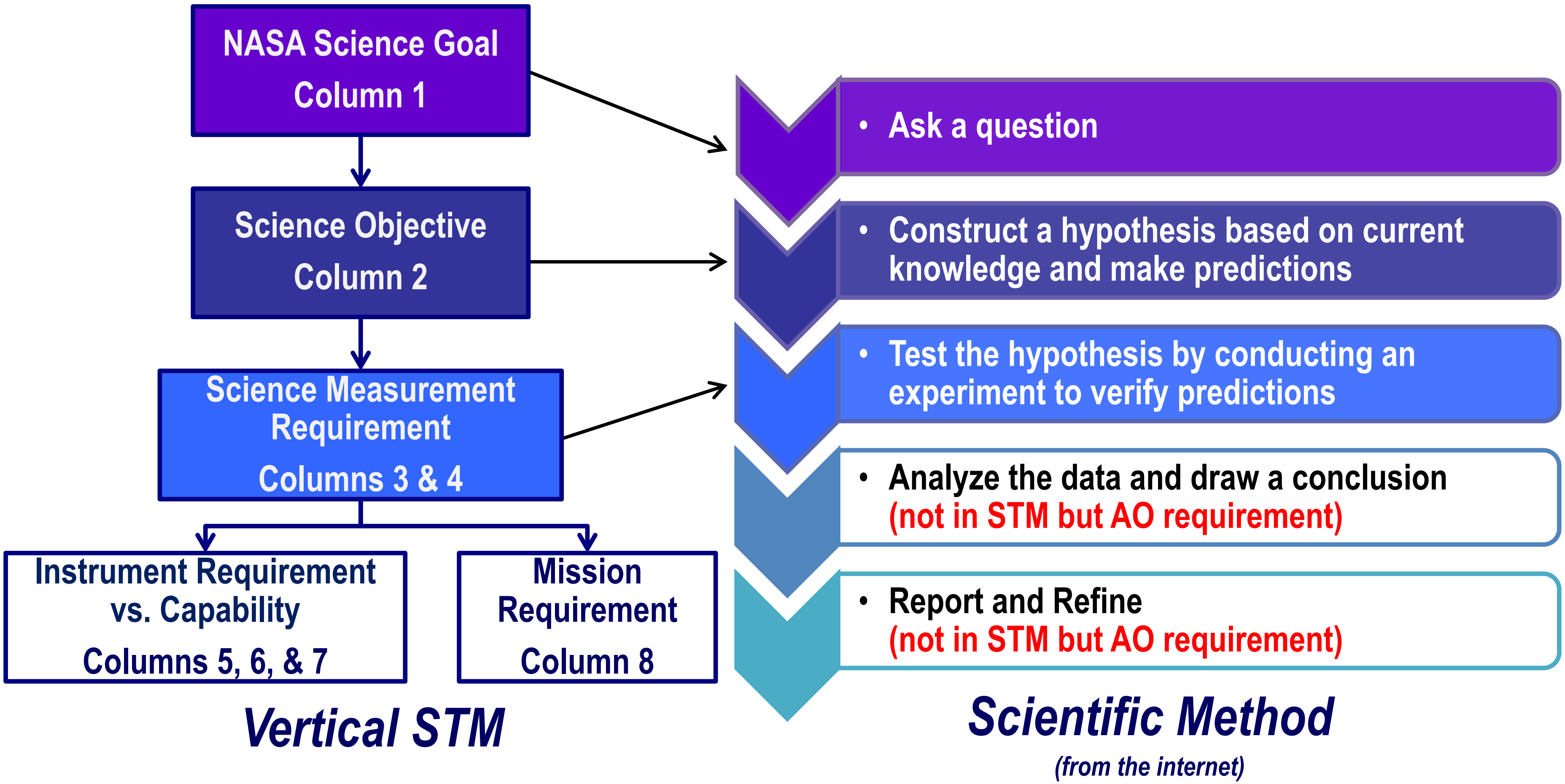


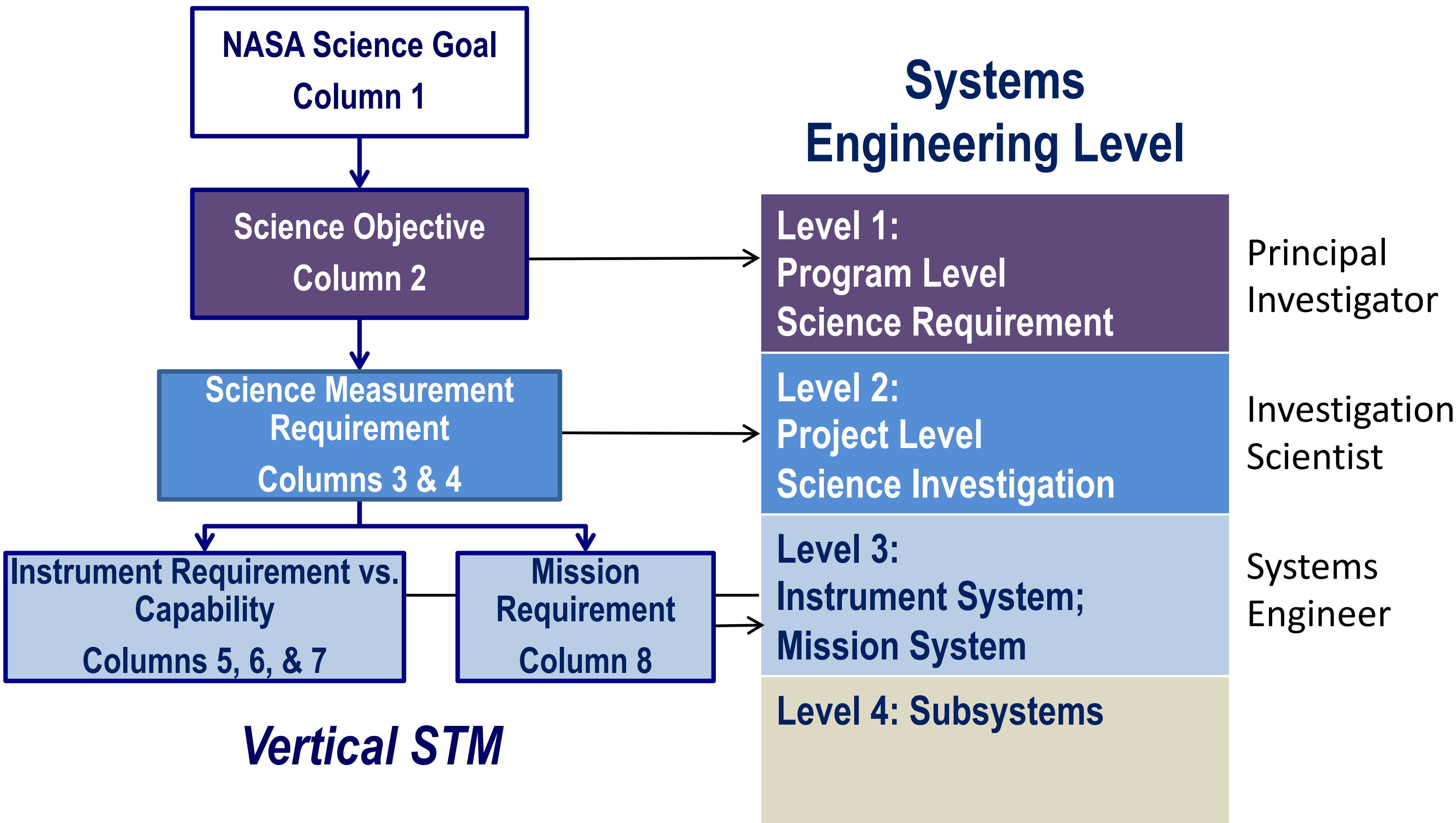
Vertical STM

STM Structure Reflects the Scientific Method

Scientific Method: systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses. (*Oxford English Dictionary*)



The STM also Maps to Systems Engineering Levels 1–3 Requirements



8 of 14 NASA Evaluation Factors Link to the STM

Scientific Merit of the Investigation:
Factor 8-1. Compelling nature and scientific priority of the proposed investigation's science goals and objectives. STM COLUMNS 1 and 2
Factor 6-2. Programmatic value of the proposed investigation.
Factor 6-3. Likelihood of scientific success. STM COLUMNS 3–4
Factor 6-4. Scientific value of the Threshold Science Mission. MUST ESTABLISH IN STM

Scientific Implementation Merit and Feasibility of the Investigation:
Factor B-1. Merit of the instruments and mission design for addressing the science goals and objectives. FLOWDOWN FROM COLUMNS 1 and 2 to STM COLUMNS 5–8
Factor B-2. Probability of technical success. CAPABILITY VS. REQUIREMENTS—STM COLUMNS 5–7
Factor B-3. Merit of the data analysis, data availability, and data archiving plan.
Factor B-4. Science resiliency. STM MUST SHOW MARGINS AND INDICATE VALUE OF THRESHOLD MISSION
Factor B-5. Probability of science team success.

TMC Feasibility of the Mission Implementation, Including Cost Risk:
Factor C-1. Adequacy and robustness of the instrument implementation plan. INCLUDES ABILITY TO MITIGATE DEVELOPMENT ISSUES BY USING DESIGN MARGIN—STM COLUMNS 5–7
Factor C-2. Adequacy and robustness of the mission design and plan for mission operations. STM COLUMN 8
Factor C-3. Adequacy and robustness of the flight systems.
Factor C-4. Adequacy and robustness of the management approach and schedule, including the capability of the management team.
Factor C-5. Adequacy and robustness of the cost plan, including cost feasibility and risk.

Commonly reported STM issues & concerns from the PI's point of view

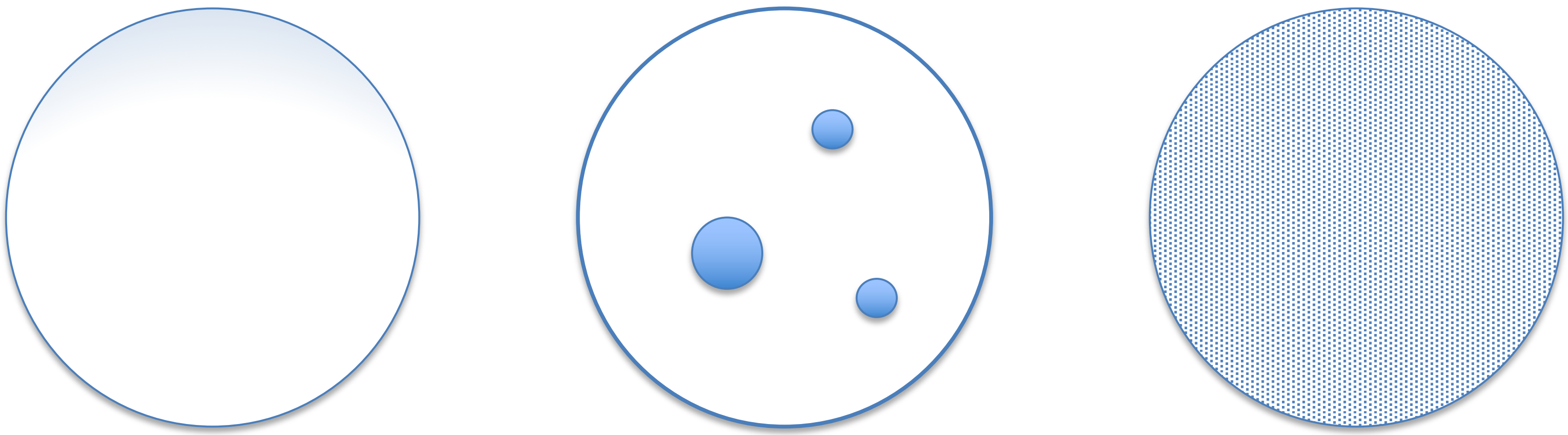
- Unfamiliar NASA expectations
  - Relatively recent change in NASA culture (especially for PIs used to directed missions)
  - Move from "get me the best instrument for the job" to "flow down instrument requirements from science"
- How to quantify exploratory science?
  - "If we don't know what we will find, how can we quantify it"
  - "If we are providing a facility, we don't want to limit it"
- Too early
  - "We aren't ready / don't need to quantitatively specify this requirement at this time; things will work out if we come back to this later"
- Lack of trust
  - "If we identify margins, then the engineering team will just take them away"

STM Column by Column
Columns 1 and 2: Goals and Objectives

- Column 1: Science goals are broad and must be identified by NASA as “high value,” as established by relevant quotes from NASA and National documents
- Column 2: Science Objectives are specific and capable of being validated.

Strongly phrased objectives start with fundamental science questions and turn them into testable hypothesis-driven predictions

Example Predictions:
Distribution of Nickel on an Asteroid's Surface



Prediction 1:
Depleted in South Polar region

Prediction 2:
Concentrated in craters

Prediction 3:
Evenly distributed across body

Strong and Weak Verbs for Phrasing Objectives

- Study… ✗
- Investigate… ✗
- Constrain… ?
- Determine whether… √
- Distinguish between… √

Columns 3 and 4:
Science Measurement Requirements –
Physical Parameters and Observables

These summarize the measured observables that will be used to determine/infer physical parameters of the body under investigation, and (for Step 2) quantify how well those parameters need to be determined to meet your science objectives.

From Nickel Distribution Example:

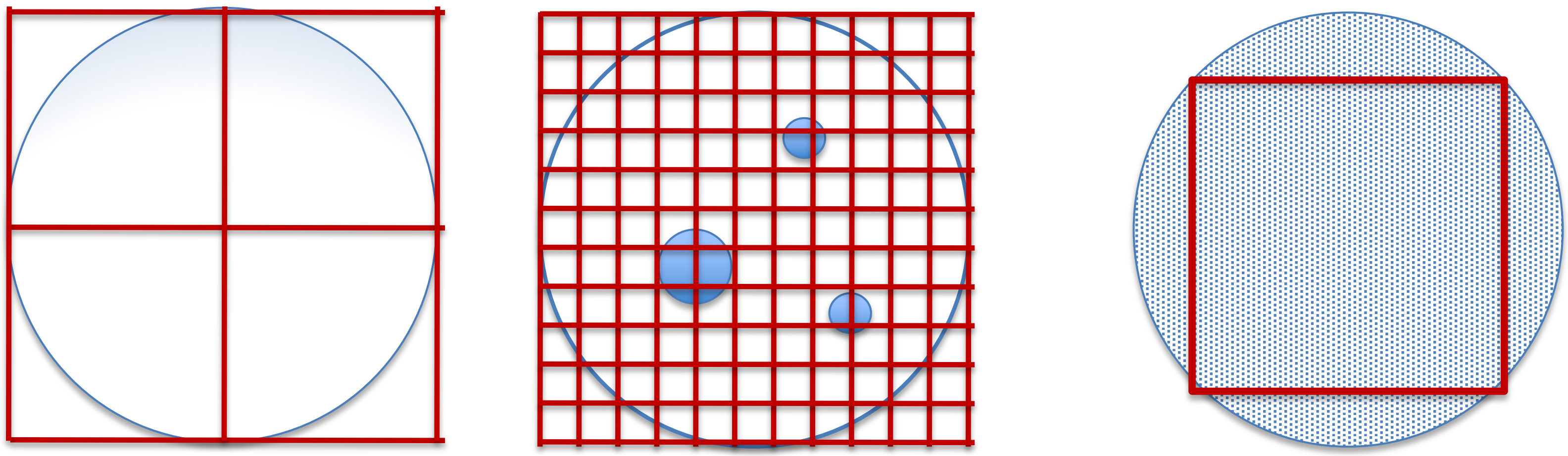
Physical Parameter = nickel distribution on the asteroid’s surface

– Real-world property of the target under investigation

Observable = nickel peaks in gamma ray spectrogram

– Measurable signal that contains information on physical parameter properties

Typical Measurement Requirements that Need to be Specified – Spatial Coverage, Spatial Resolution, Detection Limits, Measurement Accuracies



Prediction 2: Driving Case – most challenging to measure

1. Example Spatial Coverage Requirement – measure nickel gamma ray emission lines over **70%** of asteroid surface
2. Example Spatial Resolution Requirement – measure gamma ray emission signals from craters **≥10 km** in diameter
3. Example Detection Limit (one spatially resolved element): Measure Ni abundances with **SNR ≥ 6 for Nickel abundances ≥3% bulk composition by weight**
4. Example Accuracy Requirement: Determine **Ni/Fe ratio to 30% accuracy** (one spatially resolved element) for **Ni abundances ≥3% and Fe abundances >20%**

For time-variable phenomena:

Additional requirements include measurement duration & measurement frequency

Common sources of confusion: measurement accuracy vs. measurement precision vs. other similar metrics

Some measurement communities use different metrics, e.g. Root Mean Square Error of Prediction.

Important to carefully define what is needed with Science Team, and explain terminology in proposal.

Not sufficient to include precision requirement only.

STM Advice:

Look ahead to Step 2 Quantitative Level 1 Requirements when defining Step 1 Science Objectives

Look Ahead to the Step 2 (Phase A) Quantitative Requirements

- The Step 1 STM can’t be changed in Step 2 (Phase A) without potentially triggering a new Science Review—teams don’t want to go there!
- But the Step 2 Concept Study Report is required to include *much* more detailed and quantitative information on error budgets, requirements flow down, etc.—<u>calculations that impact the STM values for claimed instrument capabilities</u>
- Concentrate on common trouble areas such as detection limit requirements, accuracy requirements
- Because the Step 1 STM needs to be consistent with the Step 2 CSR, consider that
  - Science Objectives map to **Level 1** Requirements
  - Science Measurements map to **Level 2** Science and Mission Requirements
  - Instrument Requirements map to **Level 3** Payload Requirements

Step 1 Proposal Example (INSIGHT Heat Flow measurement)

Flow-down from Columns 2-4:
Science Objective to Physical Parameter to Observables

Objective

Determine whether the thermal state of the Martian interior matches Hypothesis A, Hypothesis B, or some unknown Hypothesis…

Physical Parameter

…by determining the heat flux at a single location on the Martian surface…

Observables

…by <u>measuring</u> the Thermal Gradient and the Thermal Conductivity to a depth of 3 m.

Same example, quantified for Step 2 Concept Study Report

Objective

Determine whether the thermal state of the Martian interior matches Hypothesis A, Hypothesis B, or some other unknown Hypothesis…

Physical Parameter

…by determining the heat flux at a single location on the Martian surface over the range 5-50 mW/m^2 to 10% accuracy…

Observables

…by <u>measuring</u> the Thermal Gradient to a depth of 3 m with 7% accuracy, and the Thermal Conductivity to a depth of 3 m with 7% accuracy.

More examples from INSIGHT Mars 2018 Lander –

How to turn *Qualitative* Objectives into *Quantitative* Level 1 Requirements

STM Science Objectives (Step 1 proposal)	**Level 1 Science Requirements (Step 2 Proposal)**
Determine the size, composition and physical state of the core	Positively distinguish between a liquid and solid outer core
	Determine the core radius to within ± 200 km
	Determine the core density to within ±450 kg/m^3
Measure the rate and geographical distribution of seismic activity	Determine the rate of seismic activity to within a factor of 2
	Determine the epicenter distance to ±25% and the azimuth to ±20°

Columns 5, 6, and 7: Instrument Requirements and Predicted Performance

- Columns 5 & 6: Instrument Functional Requirements address for each measurement
  - Signal intensity dynamic range and sensitivity
  - Spectral (or energy) bandwidth and resolution
  - Field of view and single-pixel Instantaneous Field of View
  - Other instrument-specific metrics

- Column 7: Predicted Performance shows instrument capability rolled up from the subsystem level (Current Best Estimate); performance margin is the difference between capability and requirement

Column 8: Mission Requirements

- The mission requirements for the STM should focus on the mission aspects that are driven by the science (e.g., not the payload mass and power)
- The flight mission has three major roles
  - Get the instrument to the place it needs to be to conduct the experiment
    - For INSIGHT: Fly to Mars, Deploy the Seismometer on the ground
  - Operate the instrument for the experiment duration
  - Get the data back to the scientists
    - Handle the data rate and volume

Strong STMs implicitly include 3 models that enable quantitative requirements to be flown down

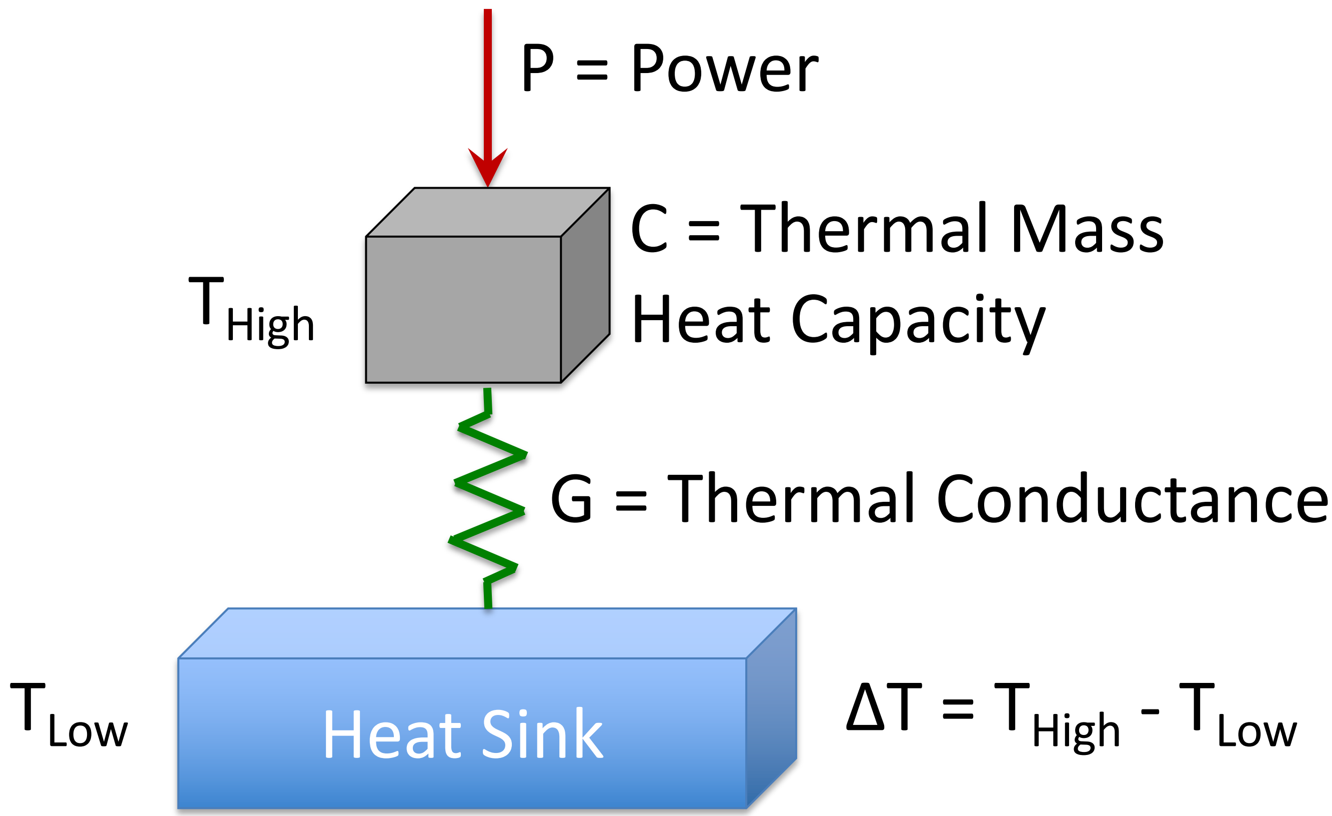
Science Model

Experiment/Measurement Model

Instrument Performance Model (flows down to subsystems not shown in STM)

NASA Science Goal	Investigation Science Objectives	Science Measurement Requirements		Instrument Performance					Mission Requirements (Science Driven)
		Physical Parameters	Observable	Parameter		Requirement	Projected		
Understand it all	Determine ppp (include space and time where appropriate)	Detect, measure, characterize, count uuu with accuracy vvv as a function of space and time	Absorption Spectrum with a SNR>xxx	Intensity	Sensitivity				Get to investigation location
					Dynamic Range				Any constraints
			for at least zzz absorption lines of uuu	Wavelength (Energy)	Bandwidth				Handle data rate and volume
			with separate identifiable peaks		Resolution				
			with spatial resolution of aaa	Angular	Resolution				Altitude
			and spatial coverage of bbb		Instantaneous FOV				Attitude (pointing)
					Pointing, scanning, etc				
			switching between the sky and the source for nnn sources	Temporal	Integration time				Operate for time duration
					Single observation duration				

“Back of the Envelope” calculations can help guide the early stages of STM development

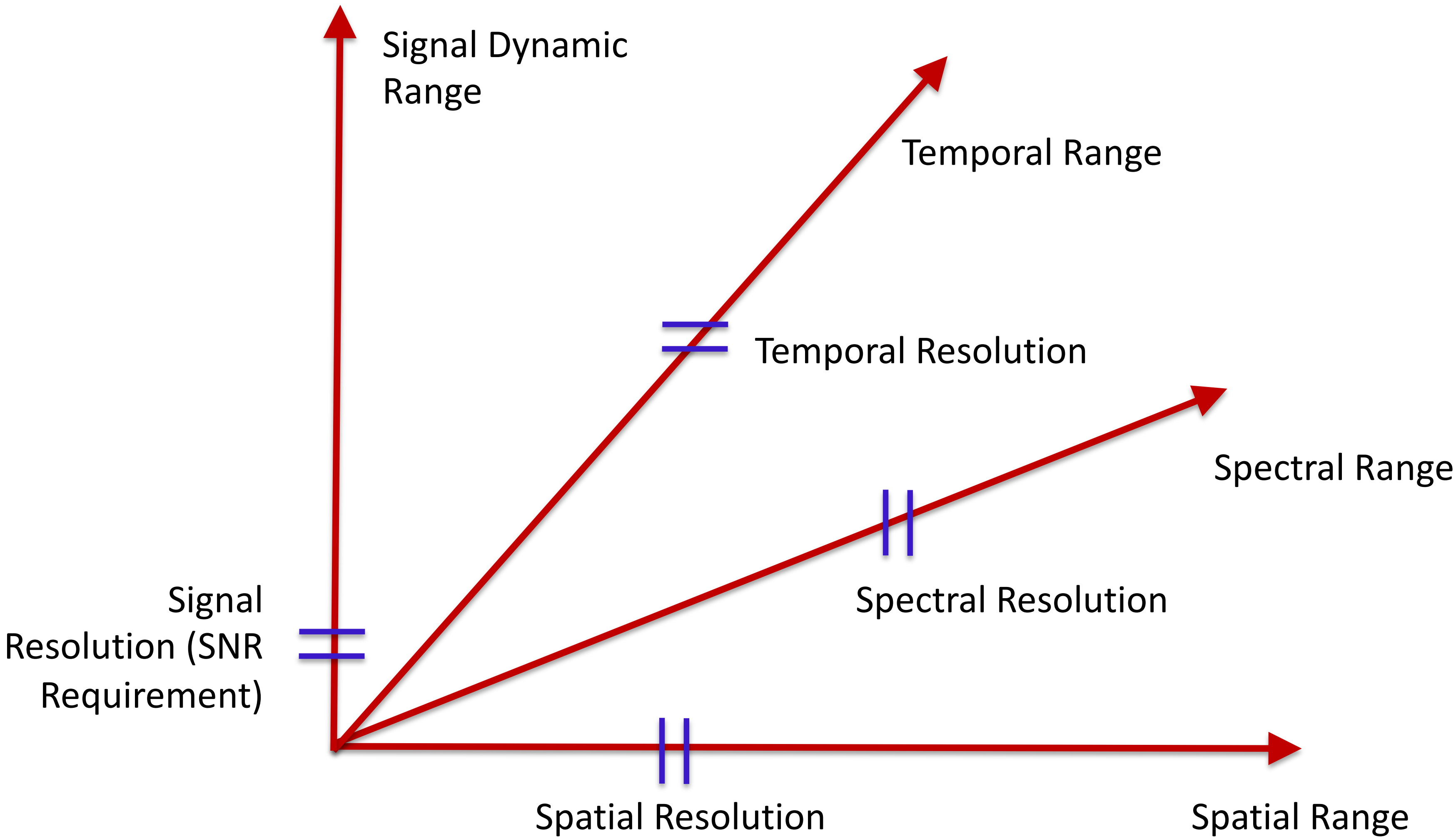


Simple Bolometer Equations:

$P = G \cdot \Delta T$

τ = Thermal Time Constant = C/G

Four “range and resolution“ axes can be helpful in generating initial set of core **driving** requirements



5 Common STM problems

1. Vague science objectives not clearly linked to science hypotheses
2. Over-constrained measurement and/or instrument requirements
3. Missing or incomplete error budgets
4. Insufficient performance margins
5. “Black Box” models: performance claims or requirements that can’t be independently verified/validated by reviewers

NASA's concerns about vague science objectives are not limited to science impact

NASA interprets vague Level 1 science requirements as a major risk factor that can negatively impact **cost** and **schedule** performance (not just **science** performance).

Actual quote from NASA debrief package:

"The Level 1 science requirements are <u>too vague</u> and cannot be used to guide the development. <u>No actual traceability</u> could be made back to L1 requirements for all flowed-down requirements. This is seen as a major risk, as adequate, robust high-level requirements are needed so that major design trades can be done and their outcomes weighed against the requirements traceability and the impact on meeting science goals."

Closing Advice:
Generate a Draft STM and Have it Reviewed Well in Advance of the Step 1 Announcement of Opportunity

- The STM is the end-product of truly understanding and articulating the science, the investigation, and the mission and instrument requirements
- The STM is the backbone that links the Science and Science Implementation Sections—develop it before the AO and those sections will flow naturally
- Generating a robust STM and having it reviewed before the Step 1 AO can help the proposal team identify and fix problem areas such as over-constrained requirements, missing error budgets, etc.
- A strong STM can guide the instrument design, maturation plan, science observing strategy, development of key proposal figures… you name it!