SPHERES

AERO ASTRO

Design Principles for the Development of Space Technology Maturation Laboratories Aboard the International Space Station

Thesis Defense

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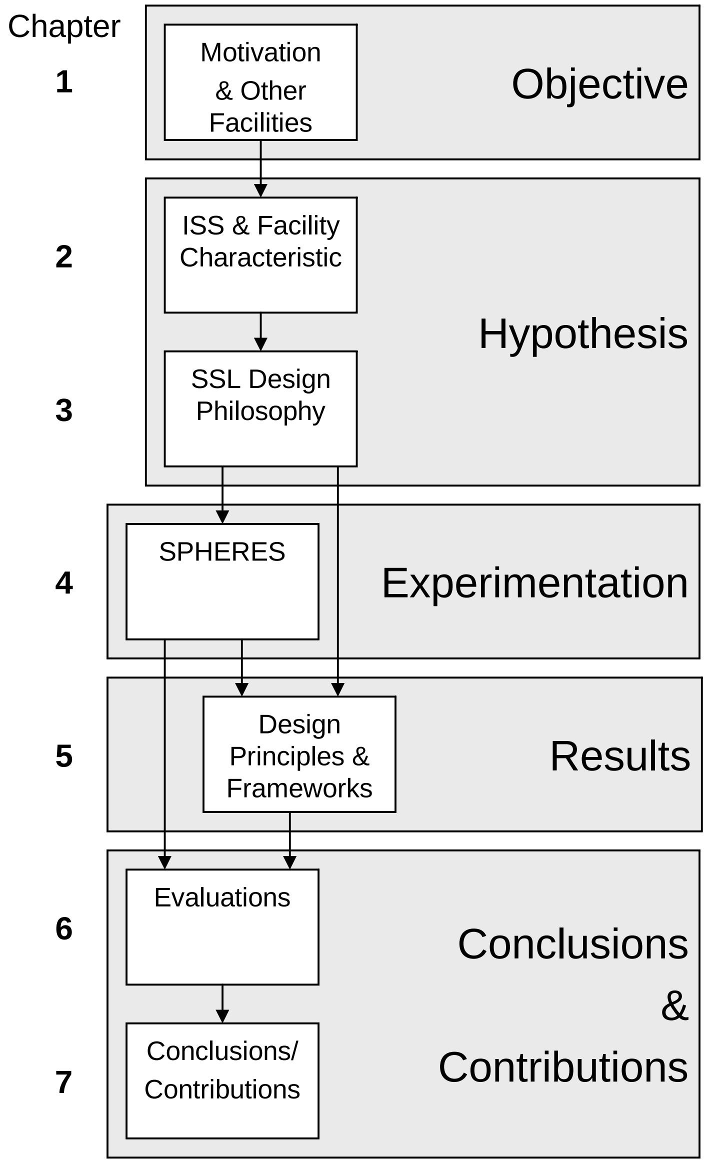
Committee Members

• Prof. David W. Miller – MIT Space Systems Laboratory	Chair
• Prof. Jonathan P. How – MIT Space Systems Laboratory	Member
• Prof. Eric Feron – MIT Laboratory for Information & Decision Systems	Member
• Javier de Luis, PhD – Payload Systems Inc.	Member
• Prof. Brian Williams – MIT Space Systems Laboratory / Minor Advisor	Member/Minor Advisor
• Prof. Jeffrey A. Hoffman – MIT Man Vehicle Laboratory	Reader
• Prof. Dava Newman – MIT Man Vehicle Laboratory/Technology Policy Program	Reader

Motivation

- Extract the design methodologies behind two decades of research at the MIT SSL in the design of facilities for dynamics and control experiments
  - What are the common design elements?
  - Which elements eased the technology maturation process?
  - Can these apply to future experiments?
  - Is there a facility for microgravity research equivalent to wind-tunnels for aeronautics research?
- National Research Council calls for the institutional management of science aboard the ISS in 1999
  - Promote the infusion of new technology for ISS research
  - Provide scientific and technical support to enhance research activities
  - Selected science use on the basis of their scientific and technical merit by peer review

Approach / Outline



Create a design methodology for the development of micro-gravity laboratories for the research and maturation of space technologies

- Review of μg and remote research facilities

The conjunction of

- The International Space Station
- The MIT SSL Laboratory Design Philosophy

present a perfect low-cost environment for the development and operation of facilities for space technology research

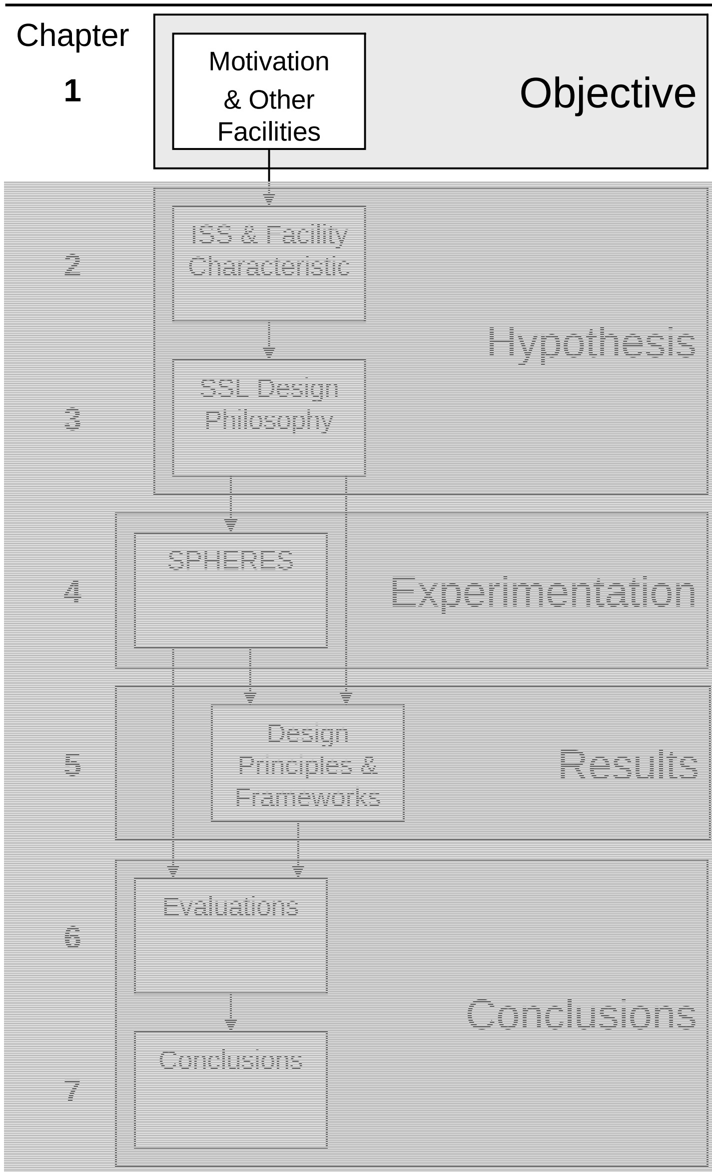
Build and operate SPHERES using the MIT SSL Laboratory Design Philosophy for operations aboard the ISS

- Description
- Iterative Research
- Support Multiple Scientists

Design Principles that guide the design of a research facility for space technology maturation utilizing the ISS

The *application of the principles* to review SPHERES indicates the Design Principles and frameworks present a valid methodology for the development of research facilities for maturating space technologies aboard the ISS

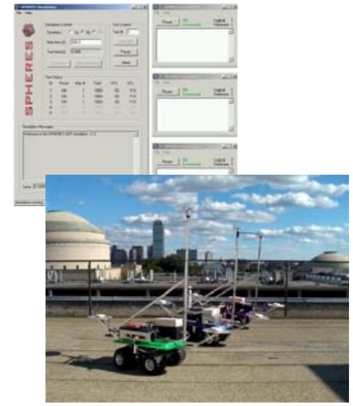
Outline



- Motivation / Approach
- µ-g and Remote Research Facilities
- The International Space Station
- MIT SSL Laboratory Design Philosophy
- SPHERES: from testbed to laboratory
  - Description
  - Iterative Research Process
  - Supporting Multiple Scientists
- Design Principles
- Application of Principles
- Contributions

μ-g Research Facilities

	DOF	Dyn.	Exp.	μg Dur.	Mis Dur.	Ops.	Data	Acc.	Cost
	Environment				Operations				
• In-house									
– Simulation	6	↓	↓	s-y	mo-y	↑	↑	↑	$
– Air table	3(5)	~	↓	m-h	mo-y	↑	↑	↑	$
– Robot Cars	3(5)	↓	↓	h	mo-y	↑	↑	↑	$
– Helium Balloons	4(6)	↓	↓	h	mo-y	↑	↑	↑	$$
– 6 DOF Robot Arms	6	↓	↓	h	mo-y	↑	↑	↑	$$$
– Robot Helicopters	4(6)	↓	↓	h	mo-y	↑	~	↑	$$
• 3rd Party Ground based									
– Flat Floor	3(5)	~	↓	h	w	↑	↑	↑	$$
– Drop Towers	6	↑	↓	s	w	~	↑	↑	$$$
– Neutral Buoyancy Tank	6	↓	↓	h	w	~	↑	↑	$$$
– RGA (KC-135)	6	~	↓	s	w	~	↑	↑	$$$
• Space based									
– Shuttle Middeck	6	↑	~	h-w	w	↓	~	↓	$$$$
– Shuttle Payload	6	↑	↑	h-w	w	↓	~	↓	$$$$
– ISS	6	↑	↑	h-y	mo-y	↓	~	↓	$$$$
– Free Flyer	6	↑	↑	mo-y	mo-y	↓	↓	↓	$$$$$



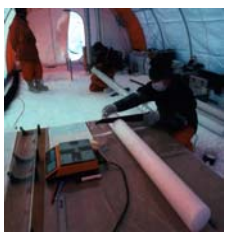
MIT SSL/ACL

JSFC RGO KC-135 - NASA

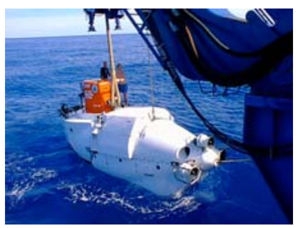
ISS - NASA

Remote Research Facilities

- Antarctic Research
  - Scientific research is primary directive *[NRC], [Elzinga, '93], [Burton, '04]*
  - International system *[SCAR]*
  - Development of shared facilities in a harsh environment *[Ashley, '04]*
- Ocean Exploration Research
  - Multiple types of research vessels *[Penzias, '73]*
  - Concentrate on conducting an experiment, not data analysis *[Cunningham, '70]*
  - Similarities with space challenges



BAS



WHOI

Allow the researcher to be in-location with facilities to conduct specific experiments

- Past Space Stations

	Crew	Duration
– Salyut	2-6	~1y (2x)
• International cooperation, EVA's		
– Skylab *[Belew, '77]*	3	<1y
• Science driven: solar exp., physiology		
– Space Lab *[Emond, '00]*	7	~2w
• International coop. aboard shuttle		
– Mir *[NASA], [Burrough, '98]*	3	~15y
• Tech. research, Earth & space sciences, biology, life support, shuttle docking, ISS Phase I		

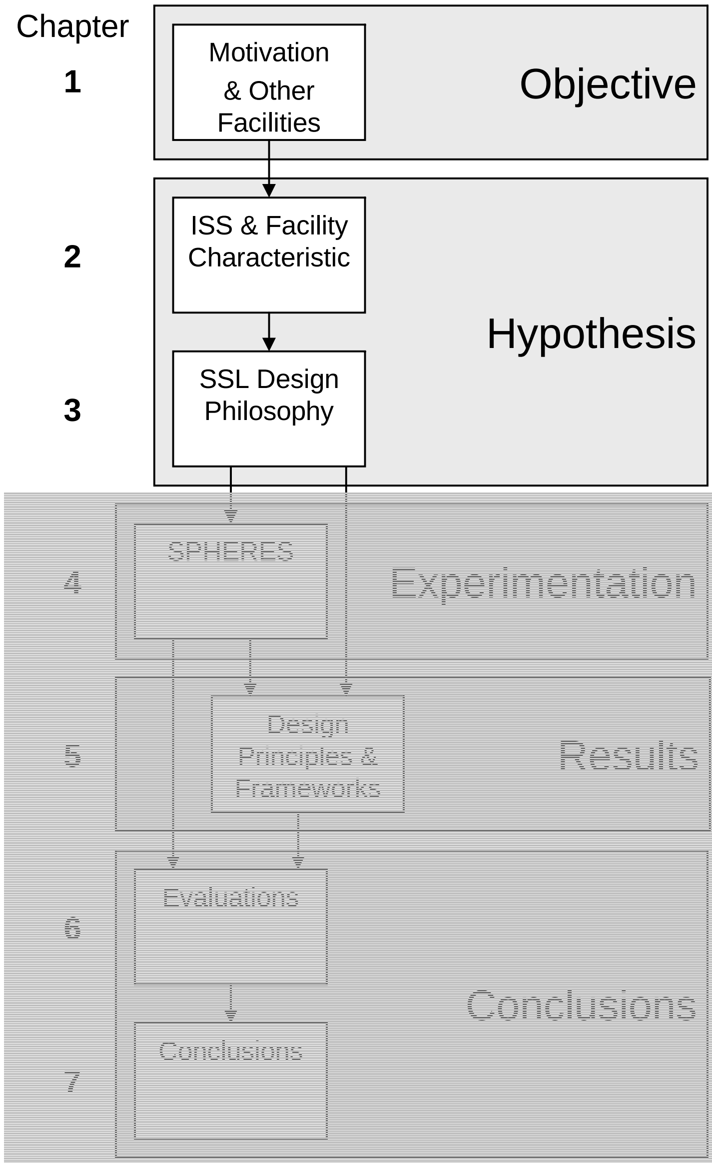
Skylab - [Belew]

MIR - NASA

Space stations do provide a unique environment for microgravity research

How do you design and build experiments to operate remotely under a microgravity environment?

Outline



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- Application of Principles
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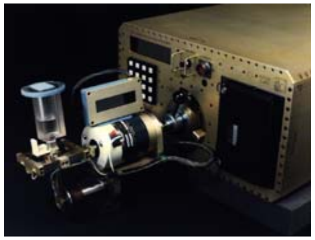
The International Space Station

The purpose of the ISS is to provide an "Earth orbiting facility that houses experiment payloads, distributes resource utilities, and supports permanent human habitation for conducting research and science experiments in a microgravity environment." *[ISSA IDR no. 1, Reference Guide, March 29, 1995]*

- Experiment Operation Types
  - Observation
  - Exposure
  - Iterative Experiments
- Major areas of study
  - Educational
  - Pure Science
  - Technology
- Special Resources of the ISS
  - Crew
    - Provide oversight of experiments, reducing the risk of using new technologies
  - Communications
    - Reduce the costs and improve the availability of data for researchers on the ground
  - Long-term experimentation
    - Enables taking many individual steps to slowly mature a technology
  - Power
    - Reduces the launch requirements (mass and cost) for missions to provide basic utilities
  - Atmosphere / Benign environment
    - Reduces cost and complexity of developing test facilities (e.g., thermal, radiation protection)

Design Philosophy (1)

- Lessons learned from past experiments
  - MODE - Middeck 0-g Dynamics Experiment
    - STS-48 ('91): fluid slush and jointed truss structures
    - STS-62 ('94): truss structures, pre-DLS
  - DLS - Dynamics Load Sensor
    - MIR: crew motion sensors
  - MACE - Middeck Active Controls Experiment
    - STS-67 ('95): robust, MCS algorithms for space structures
    - ISS Expedition 1 ('00): neural networks, non-linear & adaptive control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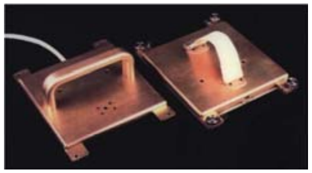
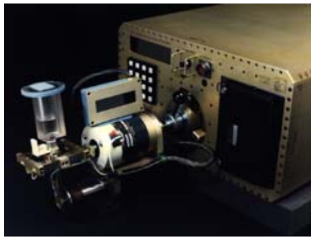

DLS

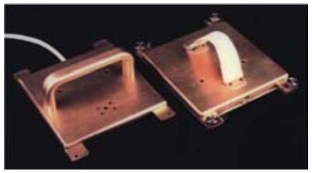

MACE

MIT SSL Laboratory Design Philosophy (1)

- Lessons learned from past experiments
  - MODE - Middeck 0-g Dynamics Experiment
    - ***Modular, generic equipment, hardware reconfiguration***
  - DLS - Dynamics Load Sensor
    - ***Extended investigations***
  - MACE - Middeck Active Controls Experiment
    - ***Multiple investigators, human observability, iterative research, risk tolerant environment, SW reconfiguration***

	Specific versus generic	Hardware reconfiguration	Extended investigations	Risk tolerant environment	Software reconfiguration	Human observe/manip	Iterative research process	Multiple investigators
MODE	✓	✓						
MODE-Reflight	✓	✓						
DLS	✓		✓					
MACE	✓	✓		✓	✓	✓	✓	
MACE-Reflight	✓	✓	✓	✓	✓			✓


MODE


DLS

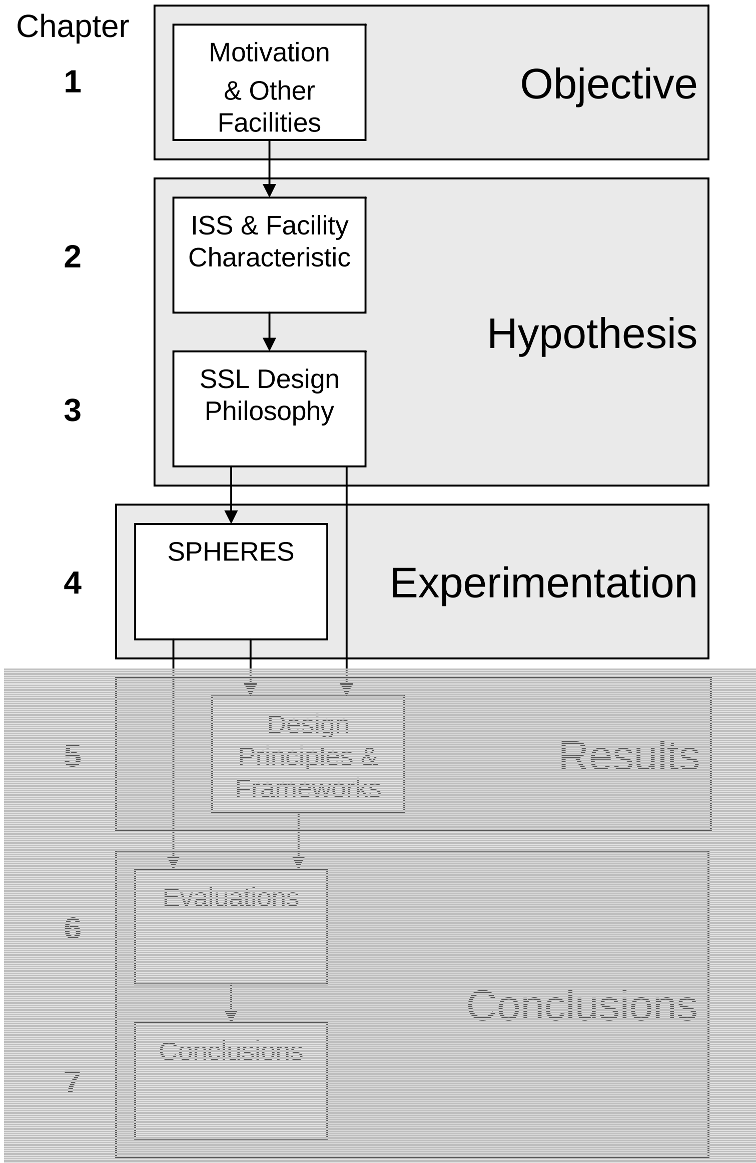

MACE

MIT SSL Laboratory Design Philosophy (2)

- The identification of these features led to the development of MIT SSL Laboratory Design Philosophy
  - Based on the need to demonstrate control and dynamics algorithms, these features guide the design of a laboratory such that the results provided in the laboratory validate the algorithms themselves, and not the capabilities of the facility

Group	**Feature**
Facilitating Iterative Research Process	Facilitating Iterative Research Process
Experiment Support	Data Feedback Precision
	Repeatability and Reliability
	Human Observability and Manipulation
	Supporting Extended Investigations
	Risk Tolerant Environment
Supporting Multiple Investigators	Supporting Multiple Investigators
Reconfiguration and modularity	Generic versus Specific Equipment
	Physical End-to-End Simulation
	Hardware Reconfiguration
	Software Reconfiguration

Outline



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- SPHERES: from testbed to laboratory
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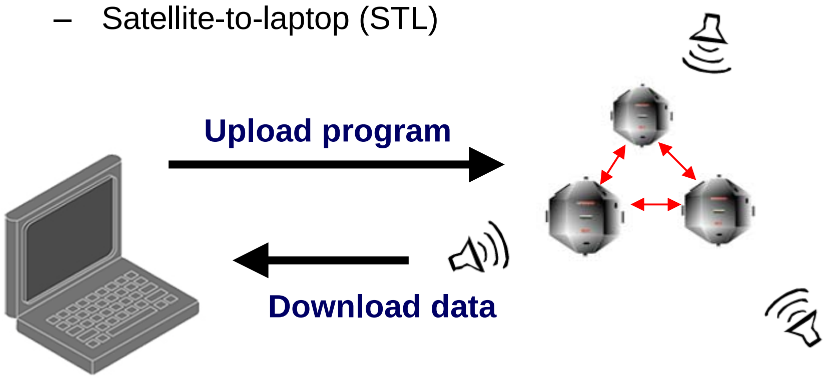
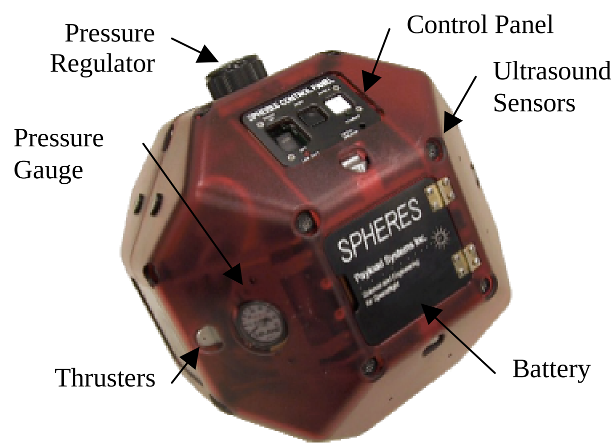
- Application of Principles
- Contributions

- **SPHERES is...**
  - **A <u>testbed</u> for formation flight**
    - Allow reconfigurable control algorithms
    - Perform array capture, maintenance and retargeting maneuvers
    - Enable testing of autonomy tasks
    - Ensure traceability to flight systems
    - Design for operation in the KC-135, shuttle mid-deck, and ISS
  - Design guided by the SSL Laboratory Design Philosophy
    - Sub-systems designed to accommodate specific features

	Lab	FF
Avionics	✓	✓
Software	✓	
Communications	✓	✓
Interface/Operations	✓	
Propulsion		✓
Structures		✓

- **SPHERES is...**
  - **A <u>testbed</u> for formation flight**
    - SPHERES free-flier units
      - Up to 5 independent units with propulsion, power, communications, metrology, and data processing
      - Sensors and actuators provide full state vector (6DOF)
    - Laptop unit
      - Standard PC laptop serves as a base station
    - Metrology
      - Five external metrology transmitters create frame of reference
    - Communications
      - Satellite-to-satellite (STS)
      - Satellite-to-laptop (STL)





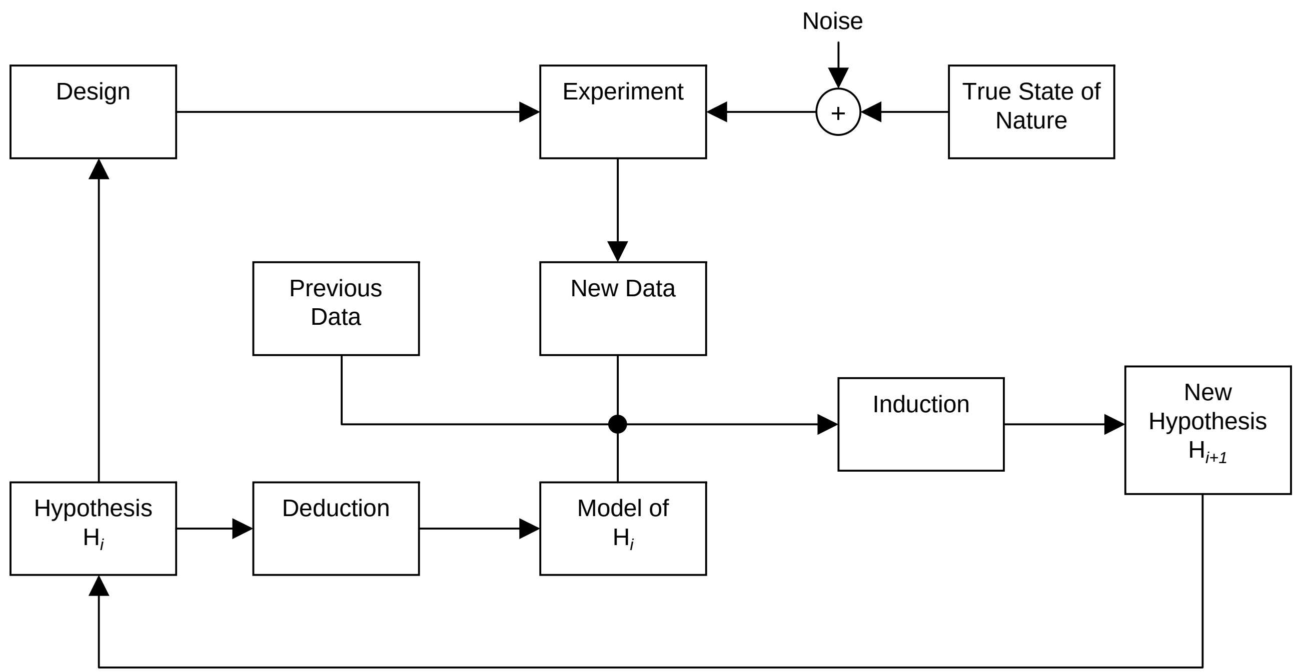
SPHERES

SPHERES Features to Meet the MIT SSL Laboratory Design Philosophy

- Facilitate Iterative Research
  - Multi-layered operations plan
  - Continuous visual feedback
  - Families of tests
  - Easy repetition of tests
  - Direct link to ISS data transfer system
  - De-coupling of SW from NASA safety
- Support of Experiments
  - Data Collection and Validation Features
    - Layered metrology system
    - Flexible communications: real-time & post-test download
    - Full data storage
    - 32 bit floating point DSP
    - *No precision truth measure*
  - Redundant communications channels
  - Test management & synchronization
  - Location specific GUI's
  - Re-supply of consumables
  - Operations with three satellites
  - Software cannot cause a critical failure
- Support Multiple Scientists
  - Guest Scientist Program
    - Information Exchange
    - SPHERES Core Software
    - GSP Simulation
    - Standard Science Libraries
  - Expansion port
  - Portability
  - Schedule flexibility
- Reconfiguration and Modularity
  - Generic satellite bus
  - Science specific equipment: on-board beacon and docking face
  - Generic Operating System
  - Physical Simulation of Space Environment
    - Operation with three units
    - Operation in 6DOF
    - Two communications channels
  - Software interface to sensors and actuators
  - Hardware expansion capabilities
  - FLASH memory and bootloader

SPHERES: Iterative Research Process

- Scientific Method Steps
  - Design
  - Deduction
  - Experimentation
  - Induction
  - New Hypothesis

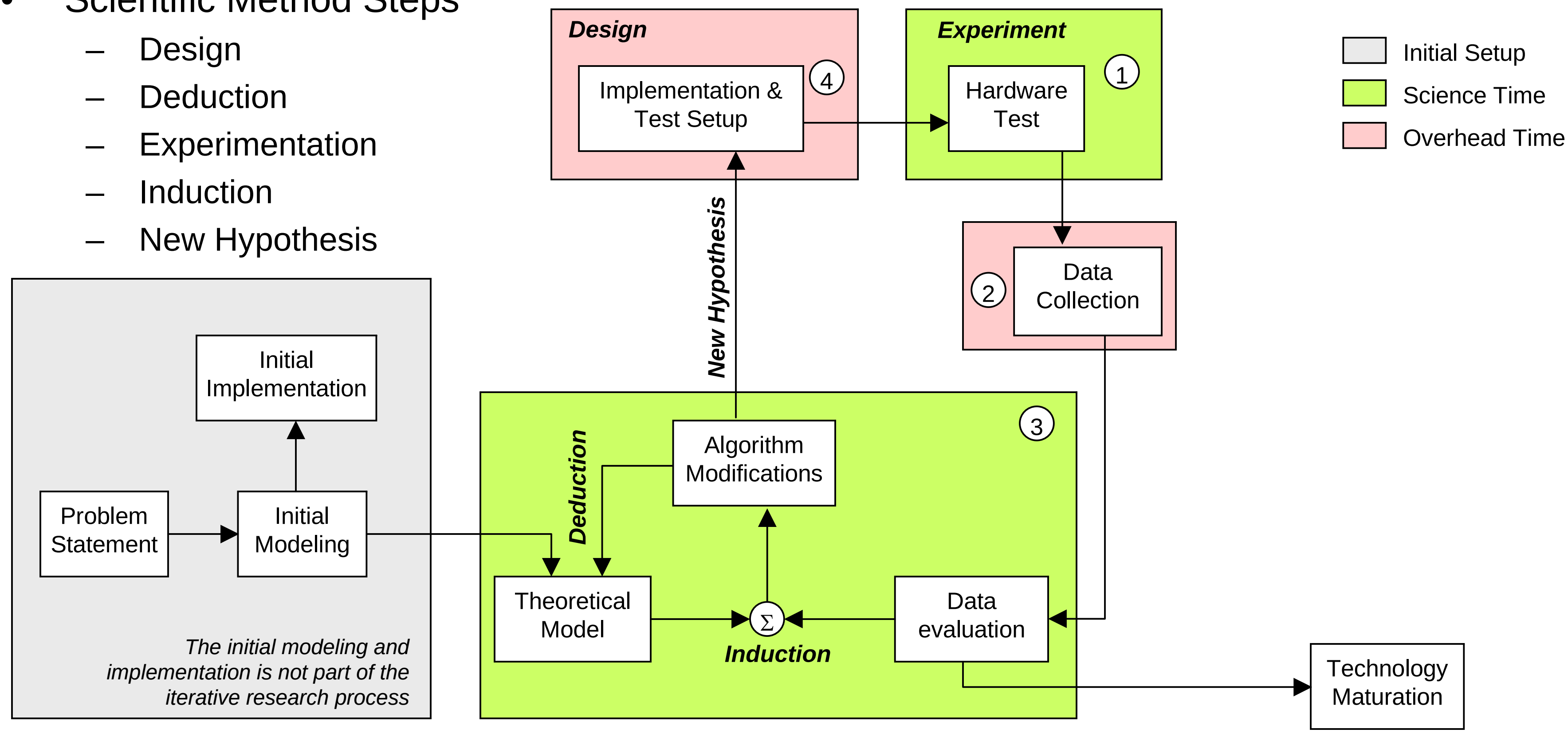


[Gauch]

*"Research is the **methodical procedure** for satisfying human curiosity. It is more than merely reading the results of others' work; it is more than just observing one's surroundings. The element of research that imparts its descriptive power is the **analysis and recombination**, the "taking apart" and "putting together in a new way," of the **information gained from one's observations**." [Beach]*

SPHERES: Iterative Research Process

- Scientific Method Steps
  - Design
  - Deduction
  - Experimentation
  - Induction
  - New Hypothesis



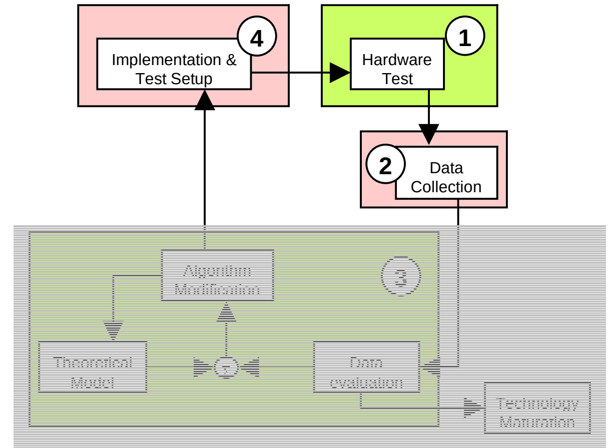
Four major steps which support the iterative process:

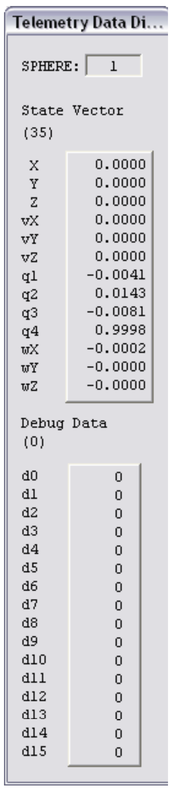
1) Test execution (science time: allow enough time)
2) Data collection and delivery to researcher (overhead time: minimize)
3) Data evaluation and algorithm modification (science time: allow enough time)
4) Modification to tests and new program upload (overhead time: minimize)

SPHERES

SPHERES: Iterations
Steps 1, 2, 4

- Continuous visual feedback
- Families of tests
- Easy repetition of tests
- Location specific GUI's
- Re-supply of consumables
- FLASH memory and bootloader



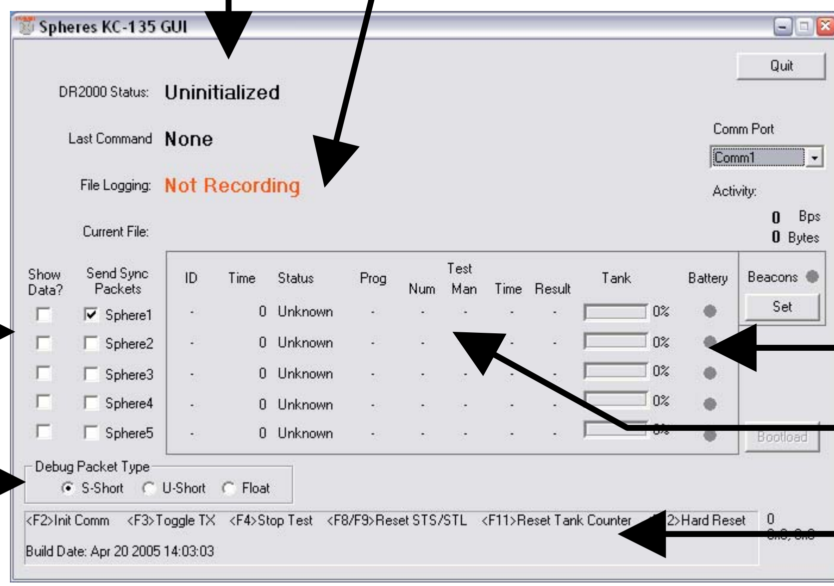


Communications status

Data recording status

Optional real-time data display

Debug real-time data



Initialization

Satellite status summary

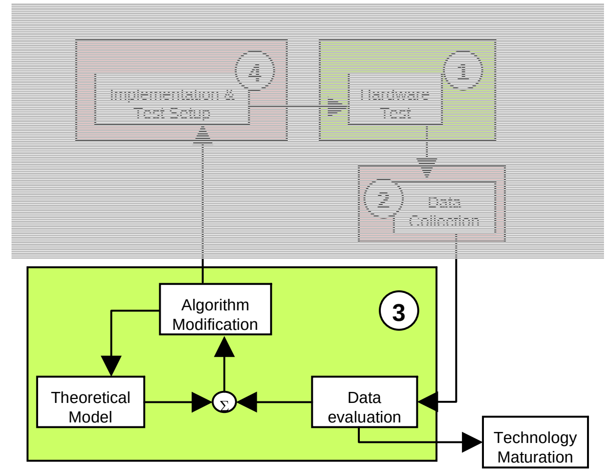
Program and test *numbers*, timing

One-key commands

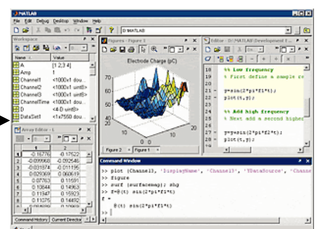
Single key test start/stop

SPHERES: Iterations
Step 3

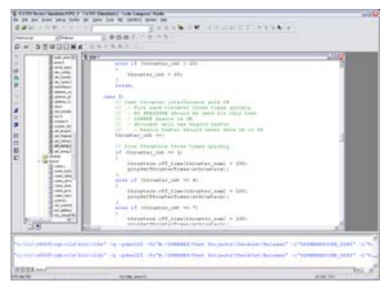
- Guest Scientist Program
  - Standard Science Libraries
- Multi-layered, multi-environment operations plan



Collect
data files



Analyze data
SPHERES provides
Matlab functions

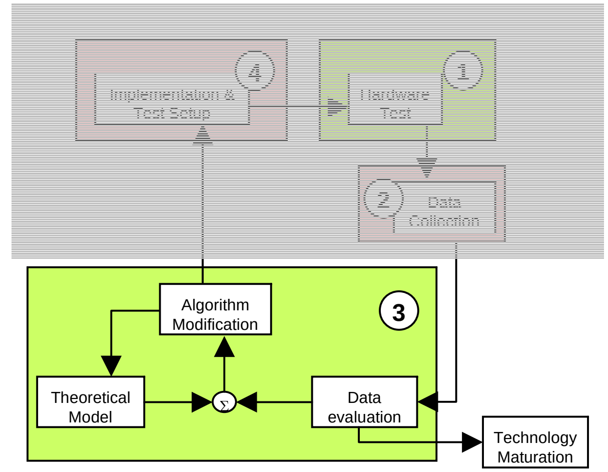


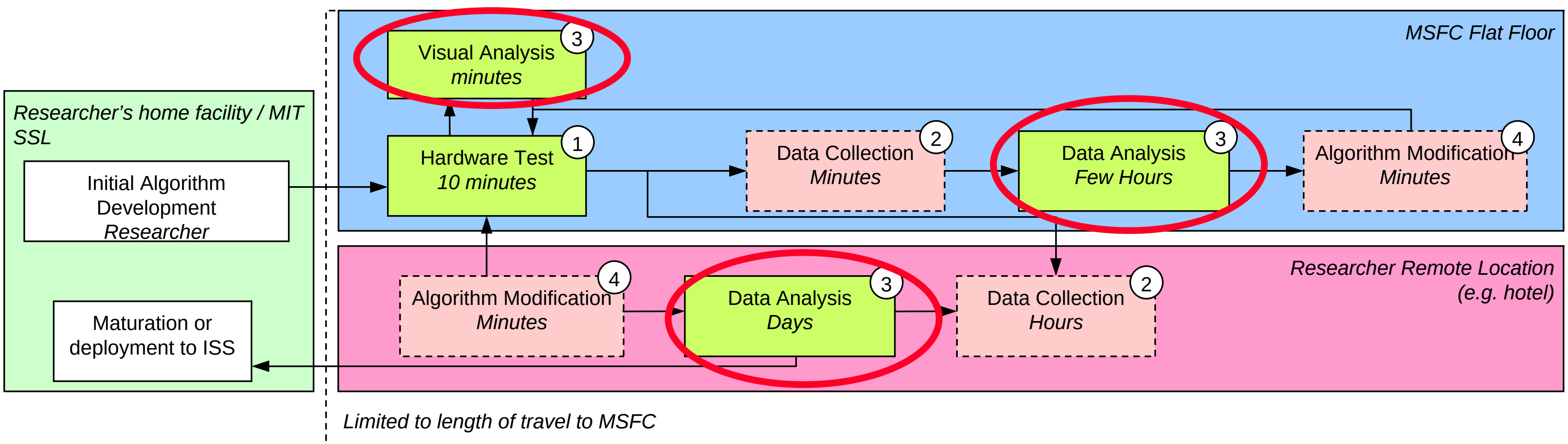
Update algorithms with CCS
C or C++

Compile new
program image

SPHERES: Iterations
Step 3

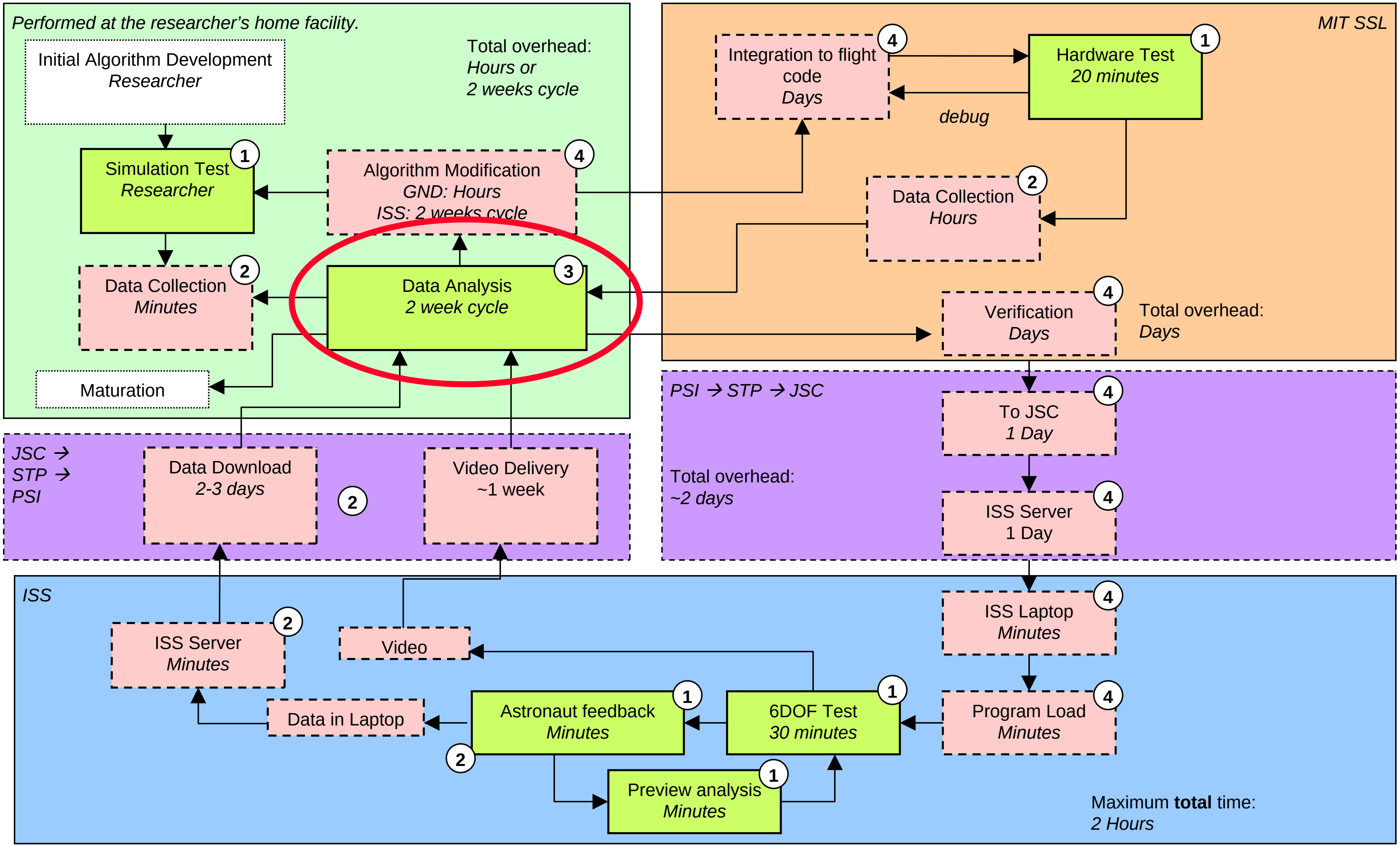
- Guest Scientist Program
  - Standard Science Libraries
- Multi-layered, multi-environment operations plan
  - Simulation: science time determined by researcher
  - SSL Off-site: science time determined by researcher and SSL availability (days/weeks/months)
  - SSL On-site: science time determined by availability / residence at SSL facilities (days/weeks/months)
  - KC-135 RGA: science time determined by parabola time (~60s), and length of stay at remote location (1-3 days)
  - **MSFC: science time determined by test operations (minutes), work day (hours) and length of stay at remote location (days)**





SPHERES

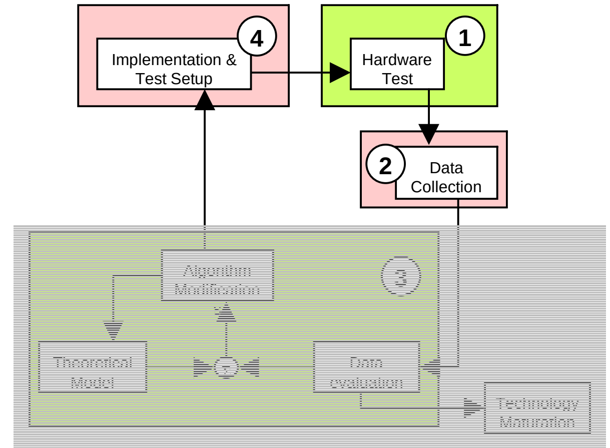
SPHERES: Iterations
ISS Steps

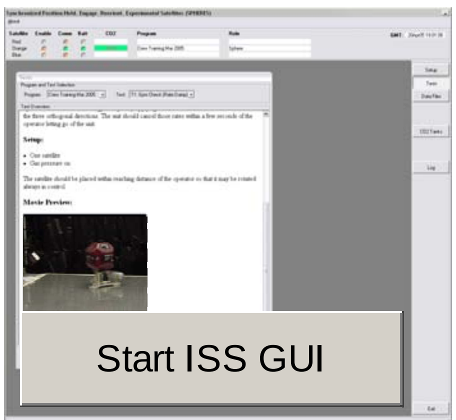


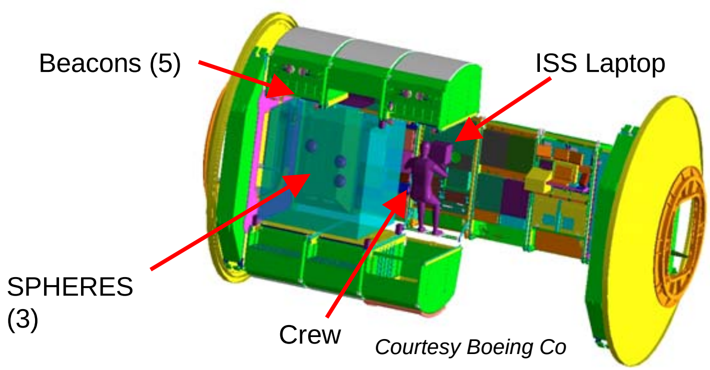
SPHERES

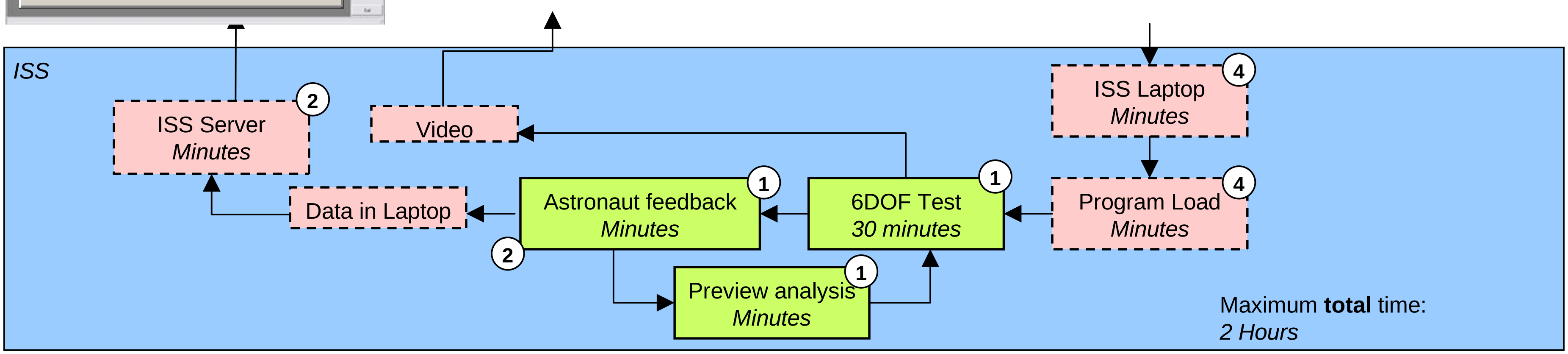
SPHERES: Iterations ISS Steps 1, 2, 4

- Direct link to ISS data transfer system
- De-coupling of SW from NASA safety
- Physical Simulation of Space Environment
  - Operation with three units
  - Operation in 6DOF
  - Two communications channels





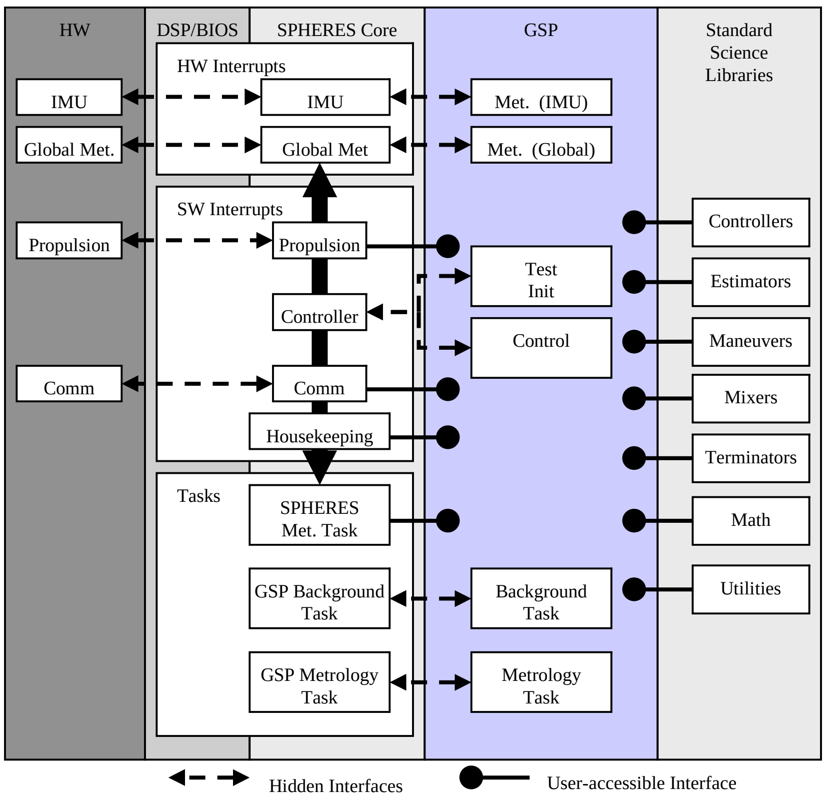


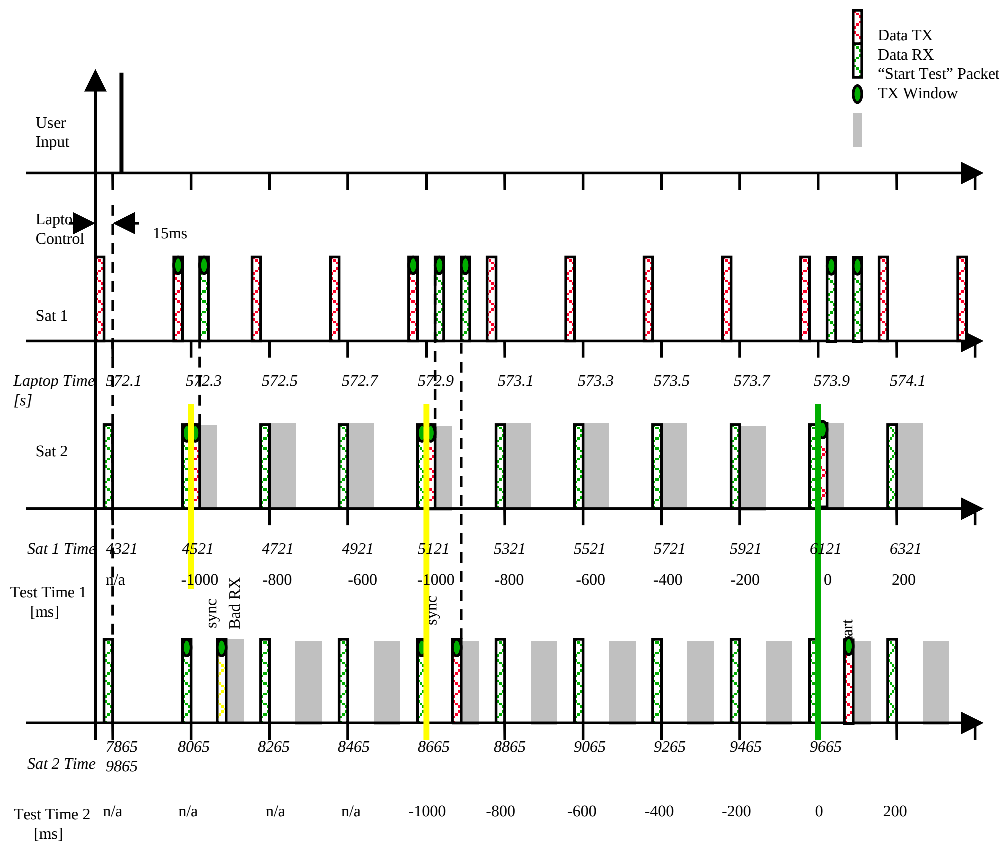


SPHERES

SPHERES: More Iterative Research Features

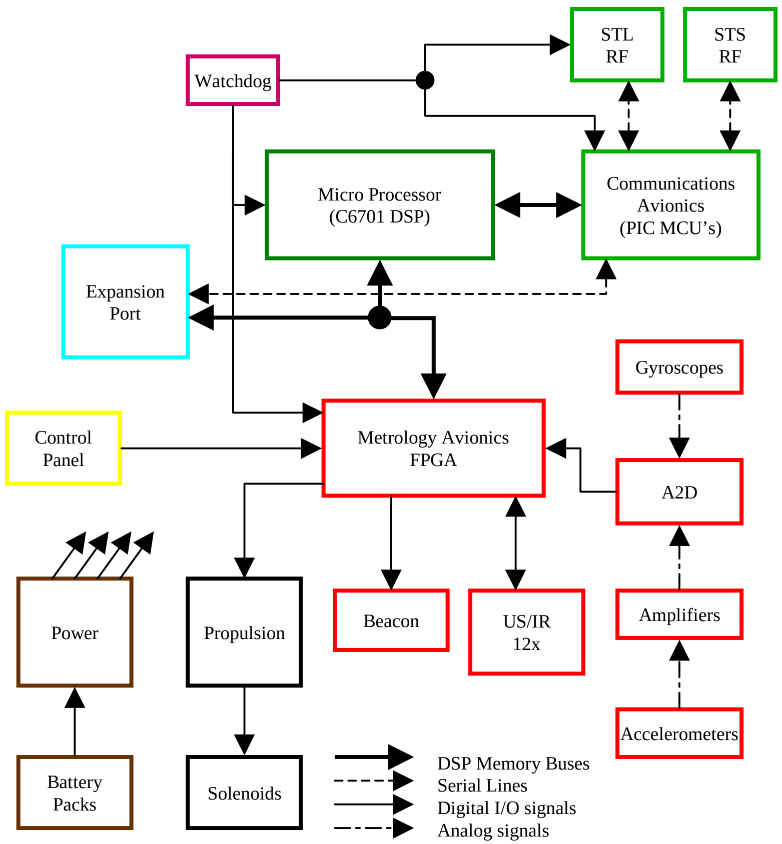
- Software (Appendix C)
  - Generic Operating System
  - Software cannot cause a critical failure
  - Test management & synchronization

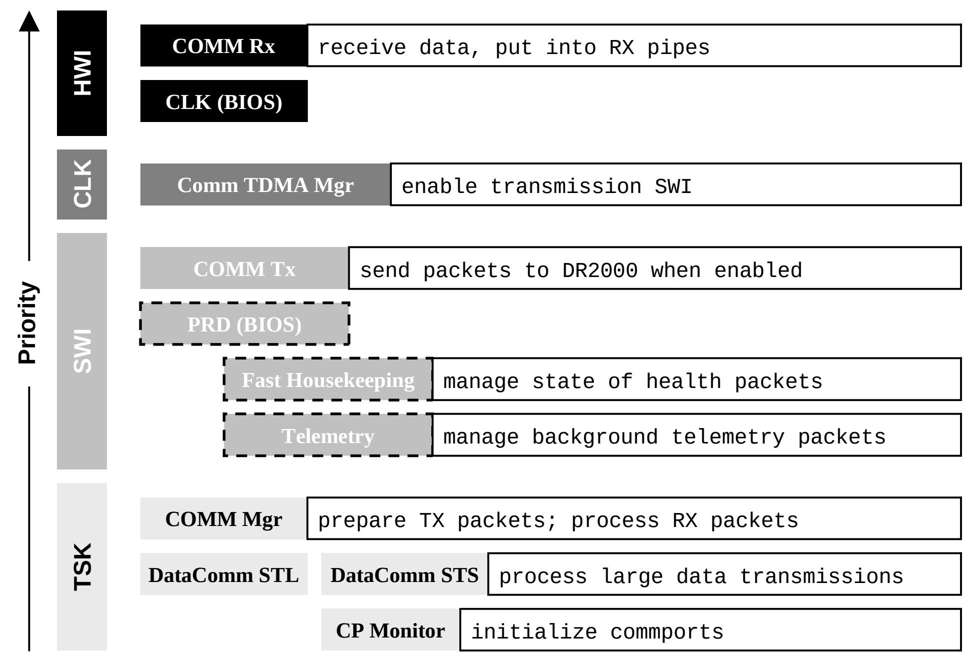




SPHERES: More Iterative Research Features

- Avionics (Appendix B)
  - Layered metrology system
  - 32 bit floating point DSP
- Communications (Appendix D)
  - Flexible communications: real-time & post-test download
  - Full data storage





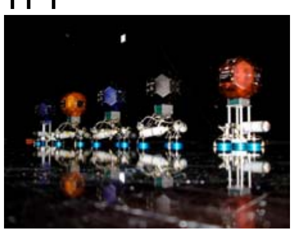
SPHERES: Supporting Multiple Scientists

- Families of tests — *Software, Operations*
- Guest Scientist Program
  - Information Exchange — *Operations*
  - SPHERES Core Software — *Software*
  - GSP Simulation — *Operations*
- Expansion port — *Avionics, Software*
- Portability — *System*
- Schedule flexibility — *Operations*

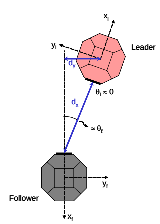
Research	Year	Application	Guest Scientist
FF Communications	2000-03	DSS	Goddard
FF Control	2000+	TPF	JPL
Docking Control	2002+	Orbital Express (DARPA)	
Mass ID / FDIR	2003+	Modeling	Ames
Tethers	2003+	SPECS	Goddard
MOSR	2004+	Mars Sample Return	

Current Programs

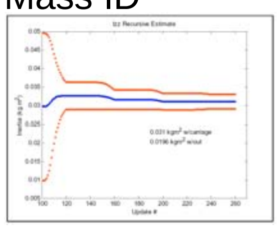
TPF



ARD



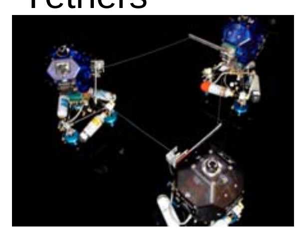
Mass ID



Future Programs

Multi-stage TPF

Tethers



MOSR

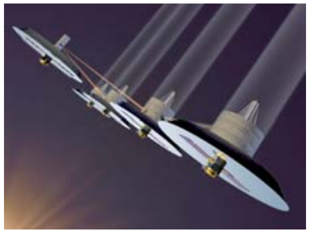
- **SPHERES is...**
  - **A** LABORATORY **for satellite formation flight**
  - The SPHERES implementation satisfies all four groups of the philosophy

Group	Avionics	Comm.	Operations	Software
Facilitating Iterative Research Process		✓	✓	✓
Experiment Support	✓	✓		
Supporting Multiple Investigators			✓	✓
Reconfiguration and modularity	✓			✓

- Laboratory: *a place providing opportunity for experimentation, observation, or practice in a field of study*
  - Therefore, by following the SSL Laboratory Design Philosophy, **SPHERES is…**
- **A separated spacecraft laboratory!**
  - *It is a reconfigurable and modular laboratory which supports conducting μ-g iterative experiments by multiple investigators*

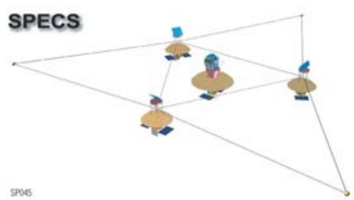
NASA

MOSR



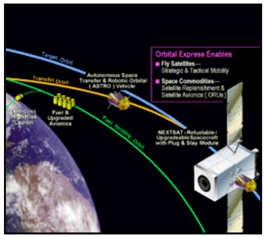
NASA

Terrestrial Planet Finder



NASA

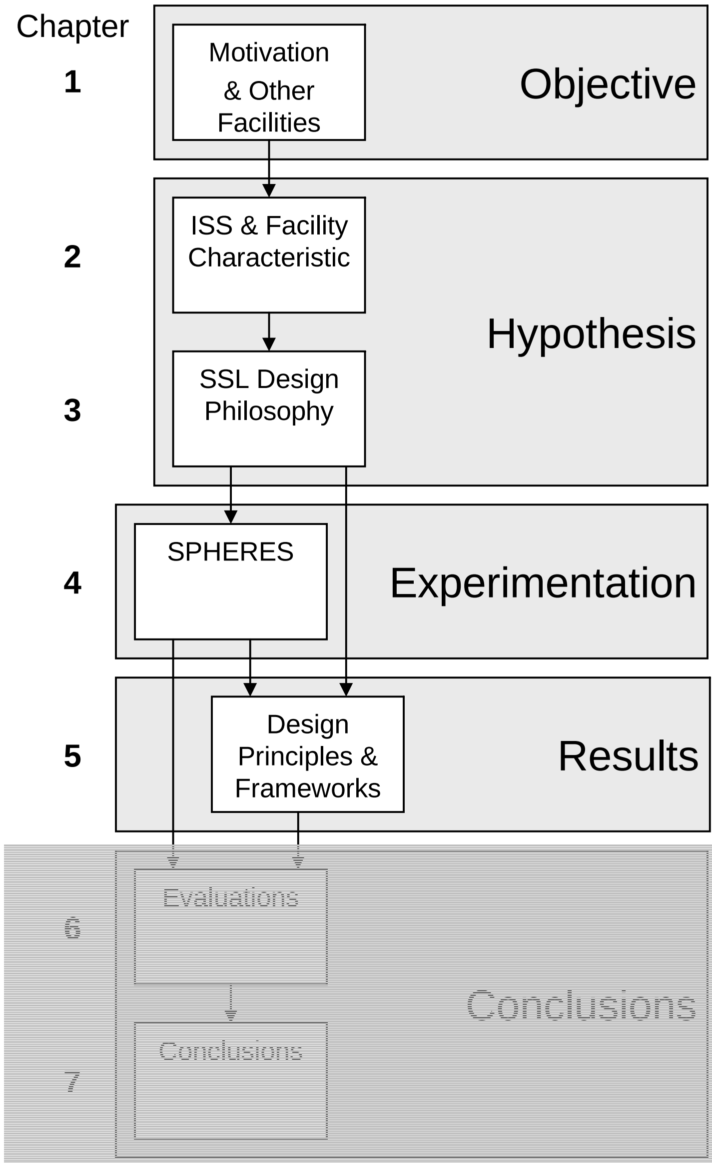
SPECS



DARPA

Orbital Express

Outline



- Motivation / Approach
- μ-g and Remote Research Facilities
- The International Space Station
- MIT SSL Laboratory Design Philosophy

- SPHERES: from testbed to laboratory
  - Description
  - Iterative Research Process
  - Supporting Multiple Scientists
- Design Principles

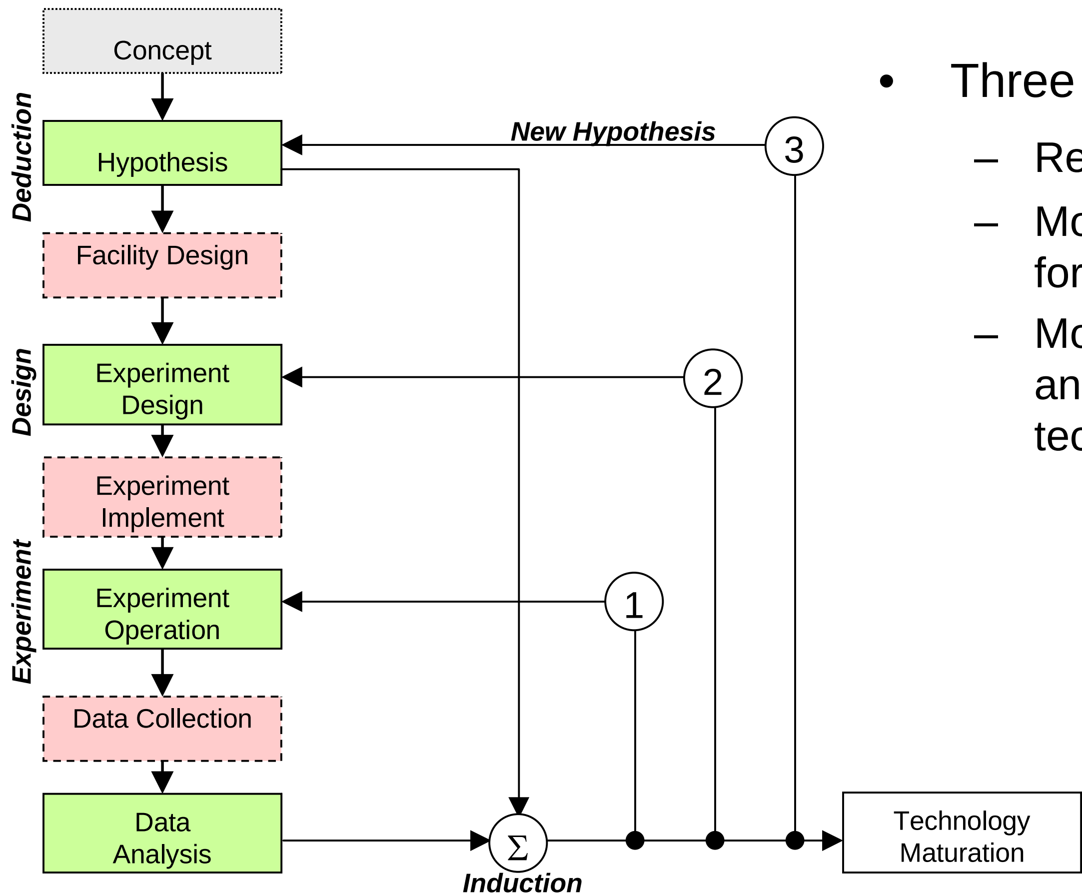
- Application of Principles
- Contributions

Design Principles for μ-g Laboratories Aboard the ISS

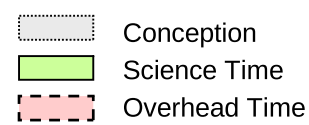
- These principles were derived from the implementation of the MIT SSL Laboratory Design Philosophy in SPHERES for operations specifically aboard the ISS
  - The principles encompass all features of the philosophy following the four main groups presented above
  - The principles incorporate the special resources of the ISS
- The following seven principles capture the *underlying and long enduring fundamentals that are always (or almost always) valid [Crawley]* for space technology maturation laboratories:
  - Principle of Iterative Research
  - Principle of Enabling a Field of Study
  - Principle of Optimized Utilization
  - Principle of Focused Modularity
  - Principle of Remote Operation & Usability
  - Principle of Incremental Technology Maturation
  - Principle of Requirements Balance

Principle of Iterative Research

- A laboratory allows investigators to conduct multiple cycles of the iterative research process in a timely fashion



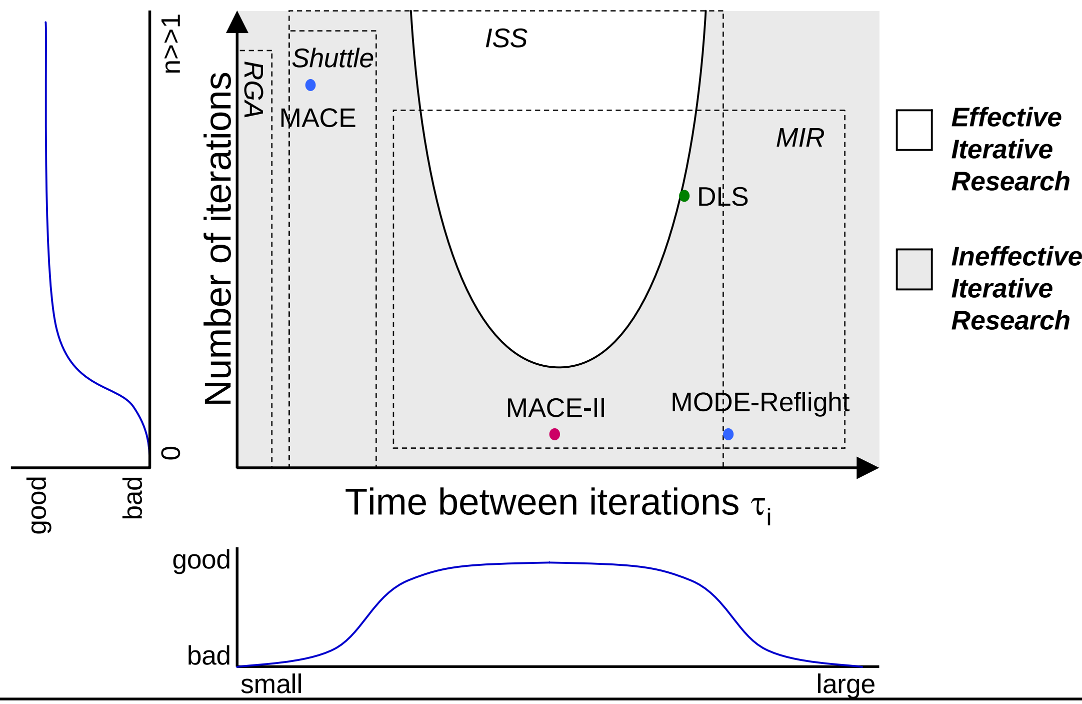
- Three iteration loops:
  - Repeat the test to obtain further data.
  - Modify the experiment design to allow for comparison of different designs.
  - Modify the hypothesis about the goals and performance requirements for the technology.



Studies the "depth" of the research

Principle of Iterative Research

- Composed of three elements:
  - Data collection and analysis tools
    - Collection bandwidth, precision, accuracy
    - Transfer rate, availability
  - Enable reconfiguration
    - To allow the three feedback loops to be closed
  - Flexible operations plan
    - Flexible time between iterations
      - Too little time prevents substantial data analysis
      - Too much time creates problems with resources and institutional memory
    - Maximize number of iterations possible



Principle of Enabling a Field of Study

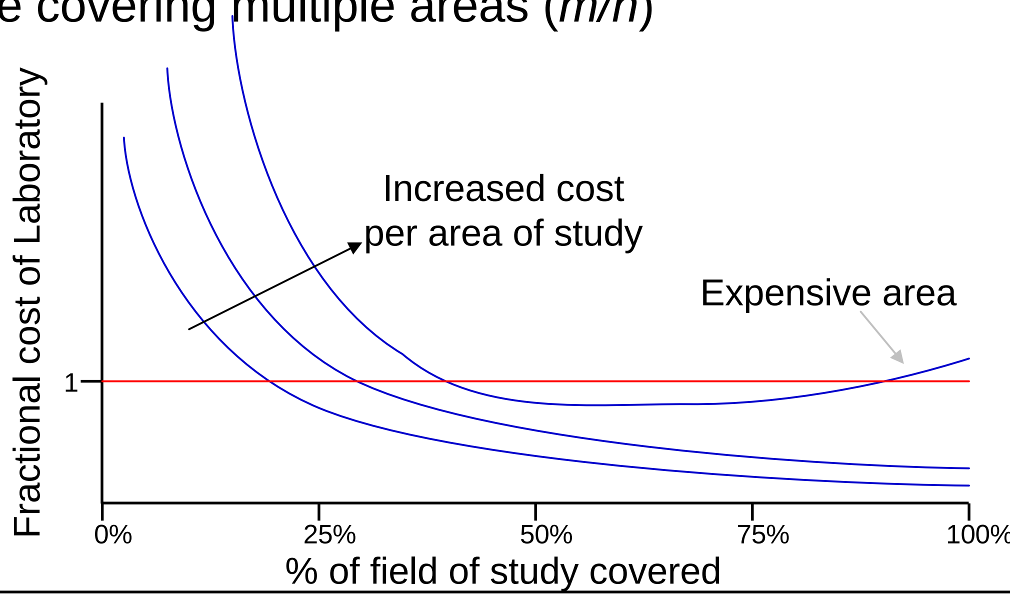
- A laboratory provides the facilities to study a substantial number of the research areas which comprise a field of study
  - Every facility must be part of a clearly defined field of study
    - The objective of a facility must clearly indicate what field of study it will cover
  - The study of multiple topics requires multiple experiments to be performed
    - Individual scientists perform research on one or a few areas
    - The work on individual topics collectively covers the field of study
    - Therefore multiple investigators, who perform experiments in their specific area of expertise within the field, must be supported
  - The laboratory must facilitate bringing together the knowledge from the specific areas to mature understanding of the field of study
    - Enable collaborative research

Covers the "breath" of the research, how much of a field of study can be covered by the facility

Principle of Enabling a Field of Study

- The methods to evaluate the efficiency of a laboratory can be compared to the methods used to determine the efficiency of *product platforms*
  - Product platform evaluations compare the cost of developing a new product with respect to the original product *[Meyer]*
  - Laboratories compare the cost of testing specific areas (k_i) in its facilities (with initial cost K_{lab}) compared to creating original facilities for each area (K_i)
  - Laboratories promote covering multiple areas (*m/n*)

$$J = \frac{m}{n} \cdot \frac{K_{lab} + \sum_{i=1}^{n} k_i}{\sum_{i=1}^{n} K_i}$$



Principle of Remote Operation & Usability

- A remotely operated laboratory, such as one which operates aboard the ISS, must consider the fact that remote operators perform the everyday experiments while research scientists, who do not have direct access to the hardware, are examining data and creating hypotheses and experiments for use with the facility

- Remote facilities are remote because they offer a limited resource that the researcher cannot obtain in their location

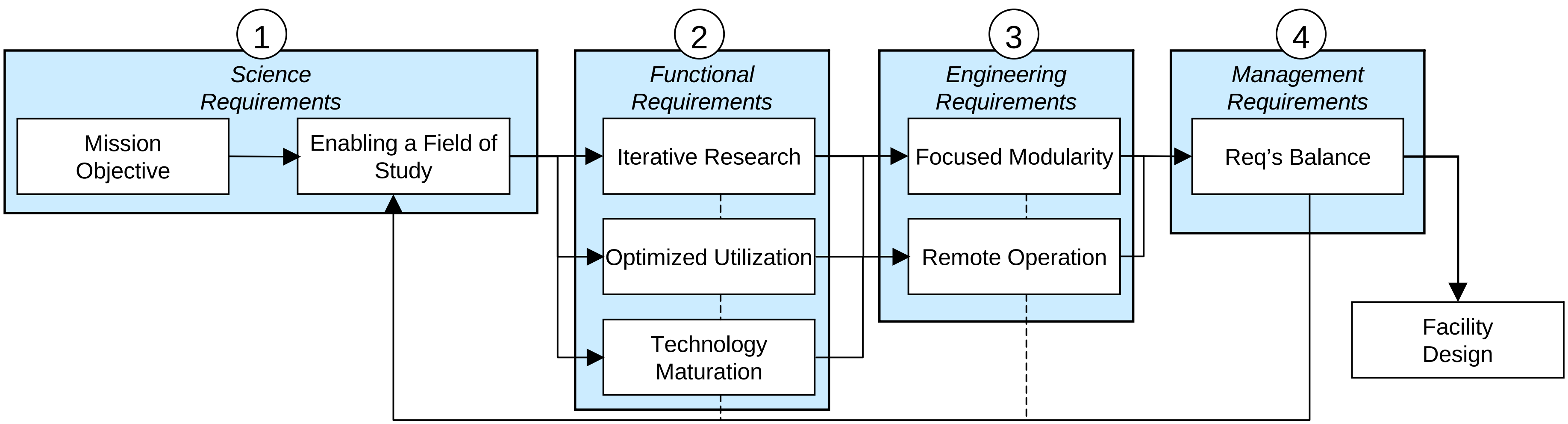
- Operators
  - are usually not an expert in the specific field
  - are an inherent part of the 'feedback' loop to provide researchers with results and information
  - are a limited resource

- Research Scientists
  - have little or no experience on the operational environment
  - are unable to modify the experiment in real-time
  - are usually an expert in the field but not in implementation
  - may not have direct contact with the facility

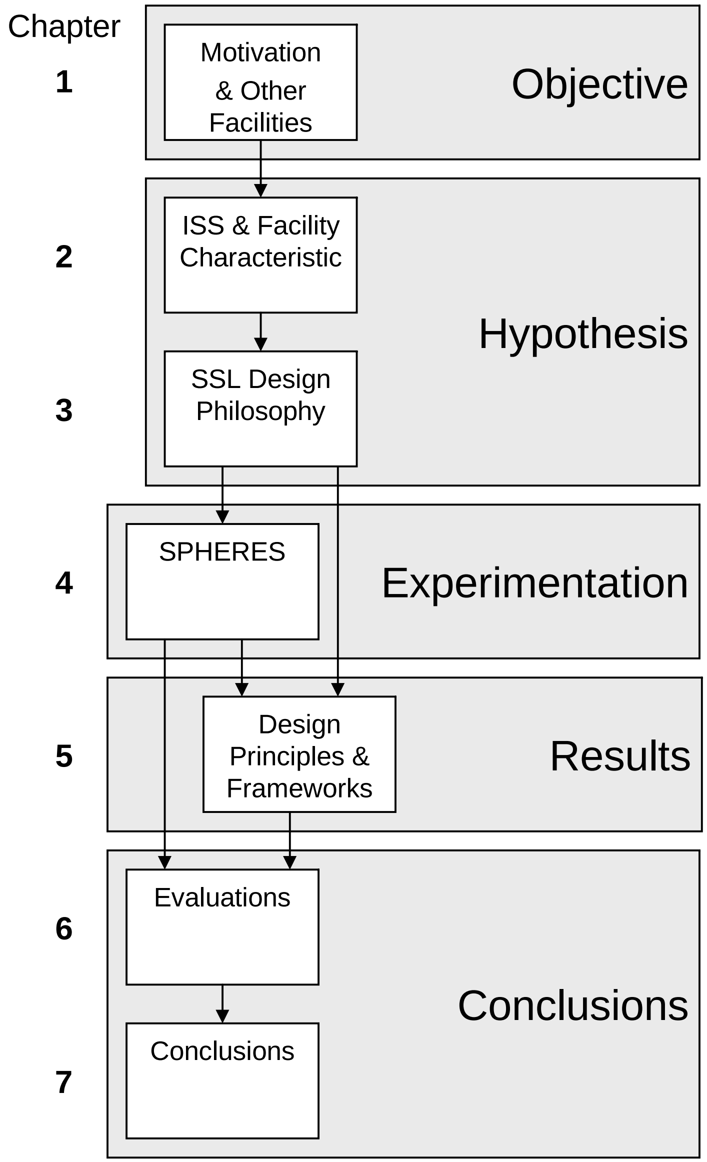
- Therefore the operations and interface of a remote facility must
  - Enable effective communications between operator and research scientist
  - Enable prediction of results
  - Ultimately: create a virtual presence of the scientist through the operator

Design Framework

- How to use the principles in a laboratory design
  - Step 1 - Identify a Field of Study
    - Select a large enough area in the field of study that the experiment can support technology maturation, but not so large that it is impossible to identify a clear set of science requirements
  - Step 2 - Identify Main Functional Requirements
    - Identify data, reliability, and schedule requirements to enhance the iterative research process
    - Define representative environment and utilization of the ISS
  - Step 3 - Refine Design
    - Identify opportunities for modularity to help both the project and the ISS program
    - Determine requirements for remote operations
  - Step 4 - Review Requirements and Design
    - Balance requirements



Outline



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Principles Applied to SPHERES

- Success
  - Enables iterative research (demonstrated)
    - Fulfills the three parts of the Principle of Iterative Research: successful data management, flexible operations plan, and enable multiple levels of repetitions and iterations
  - Supports multiple scientists (demonstrated)
    - The GSP has enabled at least six groups to participate in SPHERES
  - Utilizes most ISS resources correctly (designed, expected)
    - Designed to utilize the crew, telemetry, long-term experimentation, and benign environment features
  - Balances generic and specific equipment (demonstrated)
    - The satellite bus implemented by the SPHERES units provides generic equipment
    - The expansion port allows integration of science specific equipment
  - Creates a remote laboratory environment (demonstrated in ground, expected in ISS)
    - The portability and custom interfaces create a remote laboratory outside of the main SSL facilities
  - Allows incremental technology maturation up to TRL 6 (expected)
    - Creates the necessary representative environment to satisfy the definition of TRL 5 and TRL 6
- Recommendations
  - Design/Eval: Improve use of ISS power sources
    - While power consumption is minimal (~50W), none comes from the ISS resource
  - Design: Imbalance in resources allocated to metrology sub-system development vs. power/expansion
    - Allocation of resources (esp. man power) to metrology prevented improved design of power/expansion
  - Eval: Minimal modularity from ISS perspective
    - While modular from DSS perspective, provides no generic equipment for ISS use

Contributions: Principles

- Identified the fundamental characteristics of a laboratory for space technology maturation
  - Formalized the need for a laboratory to support iterative research
    - Based on the definition of the scientific method
    - Called for reduced dependency on DOE
  - Identified the need to enable research on a *field of study*
    - Requires support of multiple scientists in most cases
  - Advocate the use of the ISS as a wind-tunnel-like environment for μg research
- Established a set of principles to guide the design of research laboratories for space technology maturation aboard the International Space Station
  - Enables the use of the ISS to incrementally mature space technologies
  - Developed a design framework
  - Developed an evaluation framework to respond in part to the NRC institutionalization of science aboard the ISS
    - Calls for a change in attitude towards the use of resources aboard the ISS: don’t treat as costs to minimize; treat as added value, so maximize their correct use

Contributions: SPHERES

- Designed, implemented, and operated the SPHERES Laboratory for Distributed Satellite Systems
  - Multiple researchers can advance metrology, control, and autonomy algorithms
    - Up to TRL 5 or TRL 6 maturation
  - Demonstrates the implementation of miniature embedded systems to support research by multiple scientists
    - Developed a real-time operating system with modular and simple interfaces
  - Demonstrates the ability to create generic equipment
  - Enables future expansion through both hardware and software
  - Approaches virtual presence of the scientists in a remote location
    - Present the operator with the necessary initial knowledge and feedback tools to be an integral part of the research process

Questions?