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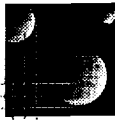
PRECURSOR SSF UTILIZATION: THE MODE EXPERIMENTS

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ABSTRACT

The MIT Space Engineering Research Center is the principal investigator for a series of experiments which utilize the Shuttle Middeck as an engineering dynamics laboratory. The first, which flew on STS-48 in September 1991, was the Middeck O-gravity Dynamics Experiment (MODE). This experiment focused on the dynamics of a scaled deployable truss, similar to that of SSF, and of contained liquids in tanks. MODE will be reflown in the fall of 1993. In mid-1994, the Middeck Active Control Experiment (MACE) will examine the issues associated with predicting and verifying the closed loop behavior of a controlled structure in zero gravity. The paper will present experiment background, planning, operational experience, results and lessons learned from these experiments which are pertinent to SSF utilization.

PRECURSOR SSF UTILIZATION: THE MODE/MACE EXPERIMENTS
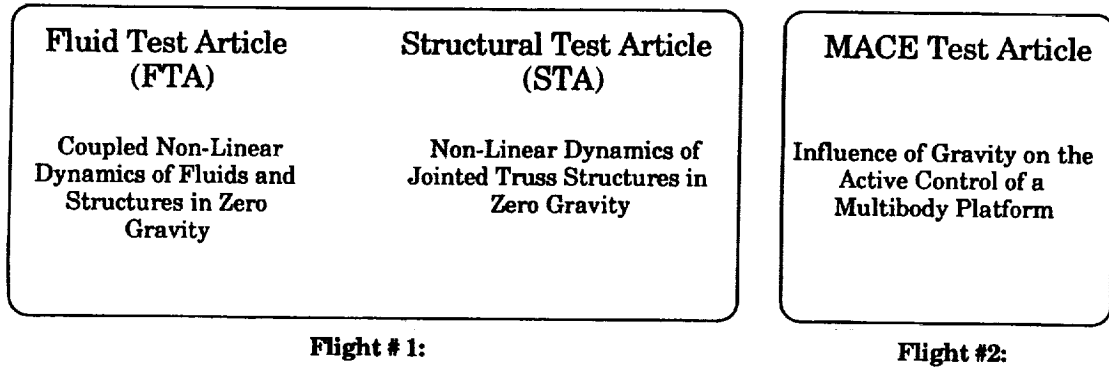
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August 5, 1992

APPROACH

- Experimental background and philosophy
- MODE STA experience
- MODE FTA experience
- MACE planning
- Lessons learned

THE MODE FAMILY OF EXPERIMENTS

Fluid Test Article (FTA)	Structural Test Article (STA)	MACE Test Article
Coupled Non-Linear Dynamics of Fluids and Structures in Zero Gravity	Non-Linear Dynamics of Jointed Truss Structures in Zero Gravity	Influence of Gravity on the Active Control of a Multibody Platform

Flight # 1:   Flight #2:

EXPERIMENTAL PHILOSOPHY

- Use the shuttle/station for engineering research (as opposed to demonstration or verification)

- Investigate (dynamics) phenomena which are influenced by gravity

- Use the Middeck Laboratory Module as a shirt sleeve lab environment with heavy reliance on crew interaction

- Use scaling laws to build model which capture the essential physics of the problem and yield results of practical value, at modest size and cost

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THE MIDDECK 0-GRAVITY DYNAMICS
EXPERIMENT (MODE)

Experimental Support Module

Test Articles

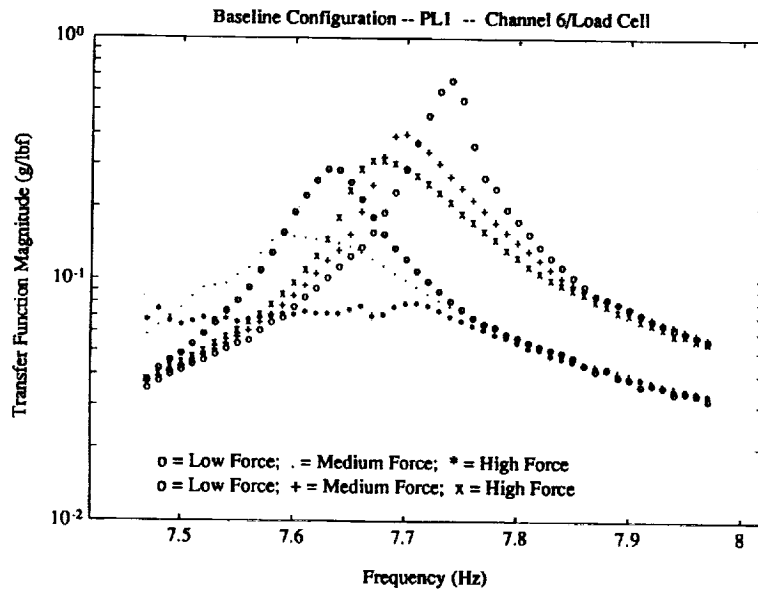| EXPERIMENT CONTROL | → | EXCITATION | → |
| DATA RECORDER | ← | DATA MEASUREMENT | ← |

Fluid Test Article (FTA)

Structural Test Article (STA)
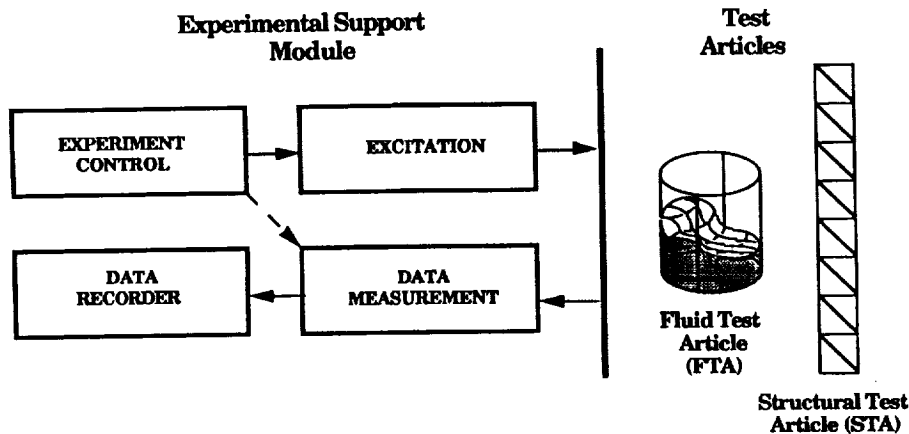
MODE provides a reusable dynamics test facility which will be used
on the first flight to test two rather different types of test articles.

STA OBJECTIVES, REQUIREMENTS & APPROACH

- Engineering science objectives are to characterize the
  fundamental changes in dynamics in 0-g due to absence of
  gravity on joints, to quantify the changes due to the absence of
  suspension and gravity load on members, and to obtain
  quantitative data for correlation with numerical models.

- Requirements

  Truss structure containing elements of future space structures.
  Nonlinear joints with variable pre-load to test nonlinear
      behavior in several gravity/joint pre-load conditions.
  Reconfigurable truss with deployable and erectable bays.

- Modelling approach

  Develop global linear model using FEM and modal test data.
  Develop Force-State Map of non-linear sub-components.
  Develop describing functions from Force-State Map.
  Insert describing functions into global model and solve for
      forced response using Harmonic Balance Method.
  Verify predictions with MODE flight and ground test results.
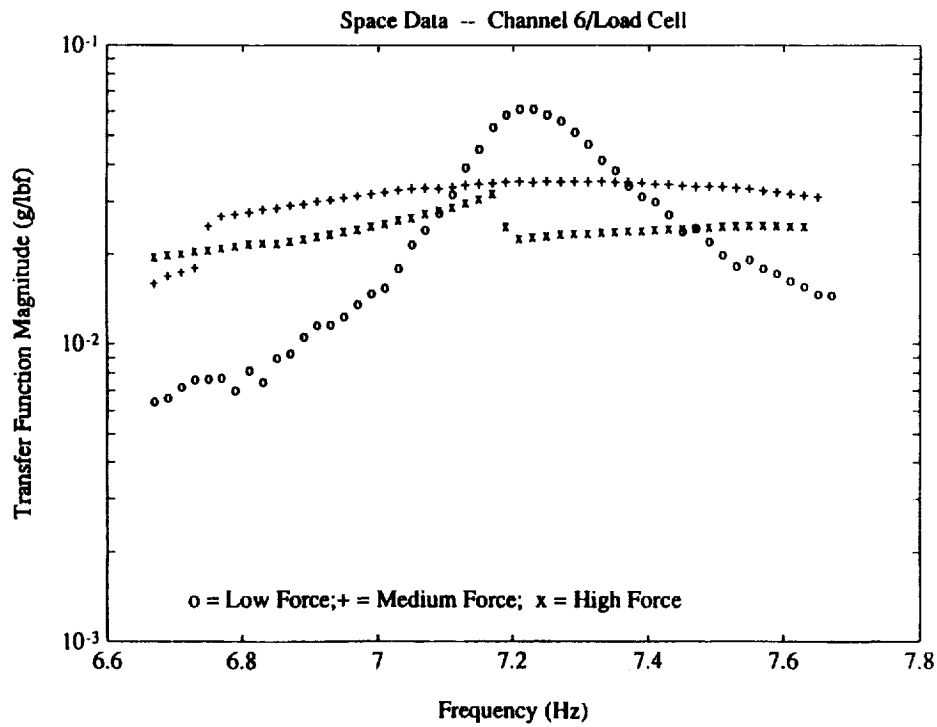
COMPARISON OF GROUND TO ORBITAL DATA FOR THE BASELINE CONFIGURATION

Baseline Configuration -- PL1 -- Channel 6/Load Cell

o = Low Force; . = Medium Force; * = High Force
o = Low Force; + = Medium Force; x = High Force

Frequency (Hz)

NOTE: Torsion Mode Only. High Pre-Load.

TORSION MODE ALPHA LOOSE

Space Data -- Channel 6/Load Cell

o = Low Force;+ = Medium Force; x = High Force

Frequency (Hz)

CONCLUSIONS OF ORBITAL TESTING

- Variation measured for erectable, deployable and articulated hardware as a function of force amplitude, joint preload and gravity loading

- Nonlinearities of the STA are more apparent in 0-gravity, especially the alpha loose, which loses resonant behavior

- Modes generally soften with increasing force, but increase in damping is significantly more pronounced

- Changes in frequency between earth and space are generally within the variance of ground testing for the baseline, but outside the variance for the alpha and L configurations.

- Changes in damping are well outside the variance of ground testing

FTA OBJECTIVES, REQUIREMENTS AND APPROACH

- Engineering science objective is to characterize fundamental 0-g slosh behavior and obtain quantitative data on slosh force and spacecraft response for correlation of numerical model.

- Requirements
    - Scaled tank
    - Properly modelled fluid
    - Simulation of coupled spacecraft mode
    - Harmonic excitation
    - Measurement of slosh force

- Modelling approach
    - Find fluid flow potential and free surface motion solutions.
    - Express kinetic and potential energies in terms of generalized coordinates.
    - Derive governing differential equations by applying Lagrange's Principle.
    - Solve nonlinear equations subject to harmonic excitation.
    - Verify predictions with MODE flight and ground test results.

Space: Water in a Flat Bottom Tank

Space: Water in a Flat Bottom Tank
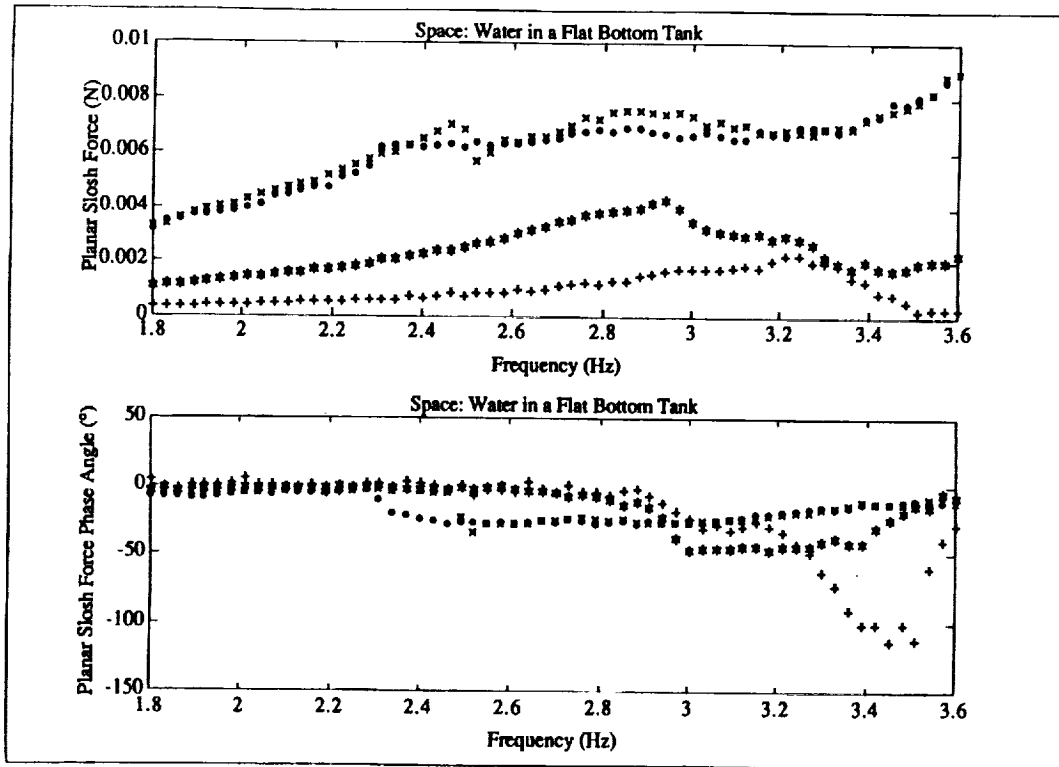
**Uncoupled Test with Distilled Water as Test Fluid in a 3.1 cm Flat Bottom Cylindrical Tank .
Planar Slosh Force.**

Space: Water in a Flat Bottom Tank

Water in a Flat Bottom Tank
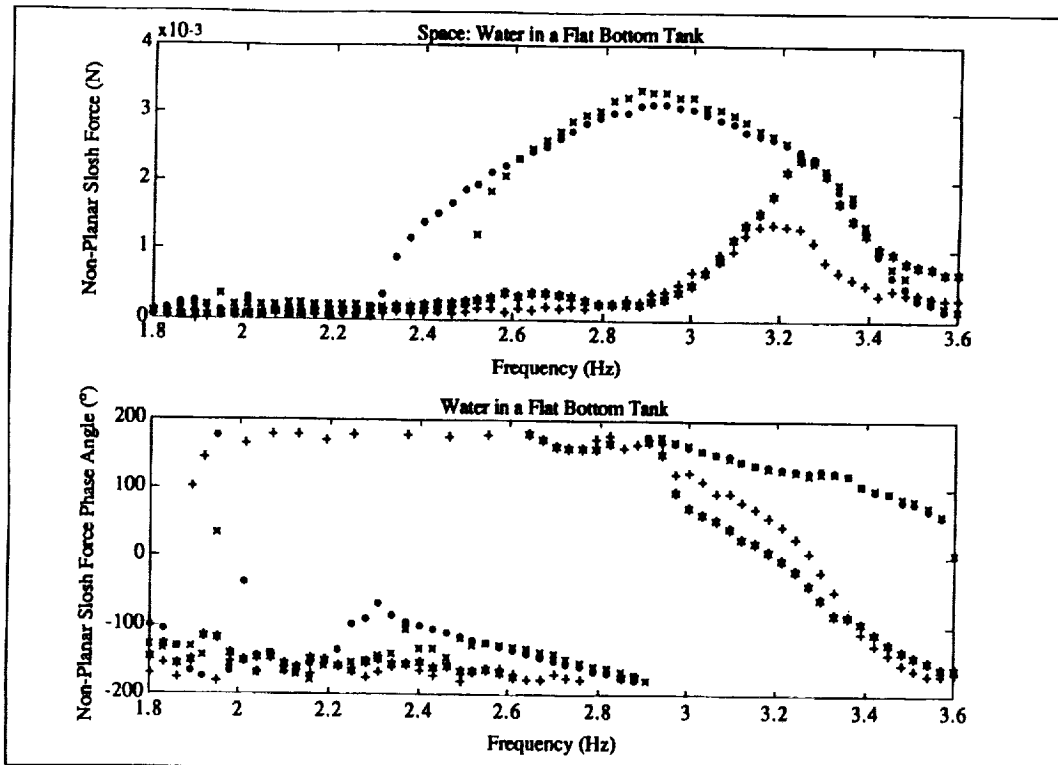
**Uncoupled Test with Distilled Water as Test Fluid in a 3.1 cm Flat Bottom Cylindrical Tank .
Non-planar Slosh Force.**

SUMMARY AND CONCLUSIONS

Space Experiments:

- More benign nonlinear behavior in space than observed on earth
- Modal damping ratios and frequencies significantly different from earth tests
- Demonstrated the ability to investigate fluid slosh in micro-gravity

Analytical Model

- Model more accurate for one-gravity conditions
- Nonlinear solution required that can find "all" the solutions
- Accurate prediction of slosh damping ratios a pre-requisite for an accurate prediction

Future

- Improve nonlinear solution technique
- More space experiments required to investigate effects of contact angle hysteresis, contact angles and dissipation rates.

MODE RESOURCE SUMMARY

Mode pushed the current Middeck capabilities:

- 115 Watts

- 3 1/2 lockers

- 60 lbs in a single locker

- 16 hours of on orbit testing

- about 25% of Middeck volume during STA testing

MACE SCIENCE OBJECTIVE

To develop a well verified set of Control Structure Interaction - Controlled Structures Technology (CSI/CST) methods and approaches that will allow designers of future CST spacecraft, which cannot be dynamically tested on the ground in a sufficiently realistic zero-gravity simulation, to have confidence in the eventual orbital performance of such spacecraft.
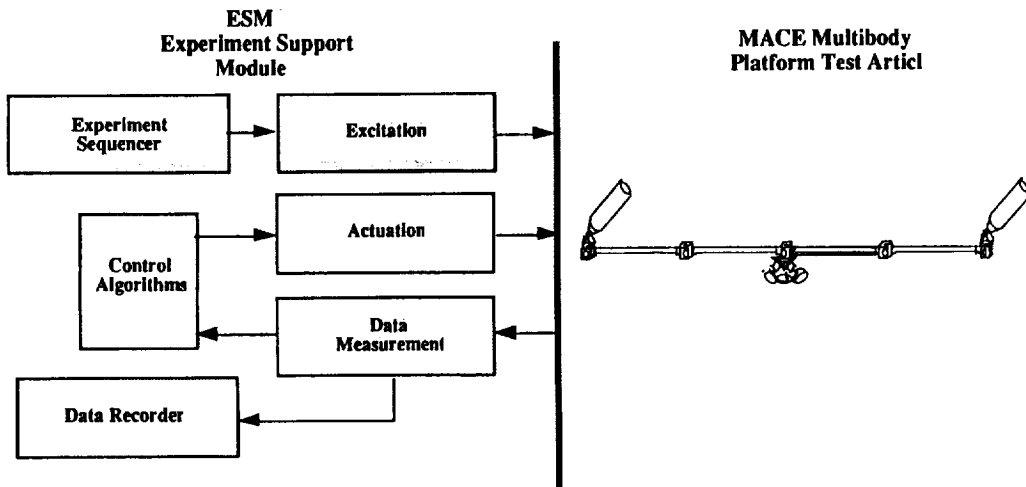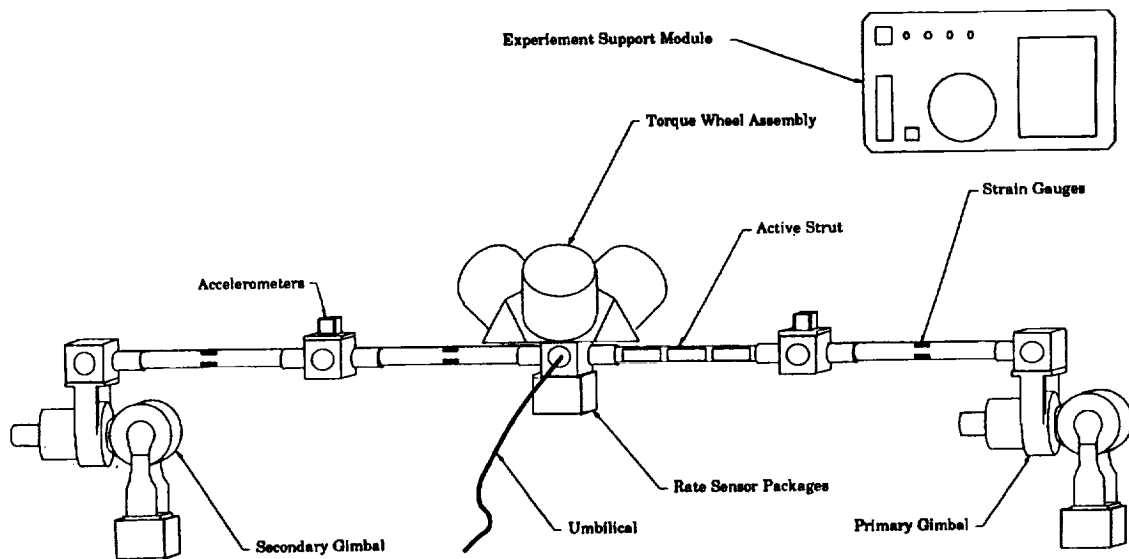
THE MACE APPROACH

- Select a test article of interest to NASA, which has near-term mission relevancy, is CSI challenging, and is sensitive to gravity perturbations.

- Dynamically scale the test article to fit in middeck in order to integrate at low cost.

- Become a pathfinder for CSI Qualification scenario:
    - Develop analytical models to incorporate the predicted gravity effects. This will lead to development of analytical CSI tools for use by future spacecraft.
    - Perform an extensive ground test program using state-of-the-art suspension systems to identify ground test limitations.
    - Perform a flight test with controllers derived from ground testing/modeling as well as from on-orbit testing.

- Transfer technology to the government/industrial sector

- Educate the next generation of engineers with a challenging, scientifically relevant project.

THE MIDDECK ACTIVE CONTROL EXPERIMENT (MACE)

ESM
Experiment Support
Module

MACE Multibody
Platform Test Articl

Experiment Sequencer → Excitation →

Control Algorithms → Actuation →

Data Measurement ←

Data Recorder ←

- Substantial commonality of ESM hardware/software

- Significant savings in integration/certification process.

MULTIBODY PLATFORM - CONFIGURATION #1

Experiement Support Module

Torque Wheel Assembly

Strain Gauges

Active Strut

Accelerometers

Rate Sensor Packages

Secondary Gimbal

Umbilical

Primary Gimbal

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ON-ORBIT OPERATIONS SUMMARY

- Operations require one crew member for three eight-hour days.

- First day operations include:
    - test article assembly and electronics check-out;
    - open-loop system identification;
    - implementation of pre-programmed control protocols;
    - system ID data reduction in preparation for downlink;
    - downlink of system identification data;
    - disassembly and storage of hardware.

- Second day operations include:
    - test article assembly and electronics check-out;
    - implementation of pre-programmed control protocols;
    - disassembly and storage of hardware.

- Third day operations include:
    - test article assembly and electronics check-out;
    - uplink of system identification data-based controllers;
    - implementation of uplinked control protocols;
    - disassembly and storage of hardware.

RESOURCE SUMMARY

RESOURCE		ACTUAL	TARGET	SSP LIMIT
Power		470 Watts	600 Watts	1000 Watts
Mass				
	ESM	57.3 lbs	59.0 lbs	68 lbs
	Test Article	86 lbs	100 lbs	162 lbs
Volume				
	Stowed	4 lockers	5 lockers	negotiable
	Operational	70 ft^3	70 ft^3	negotiable
Operations				
	Crew Members	1	1	negotiable
	Crew Time	3x8 hr days	3x8 hr days	negotiable
	Crew Training	?	28 days	negotiable
	Uplink (modem)	1 hr.	1 hr.	negotiable
	Downlink (Ku band)	4 mins.	8 mins.	negotiable
	Downlink (modem)	2 hrs.	2 hrs.	negotiable

MODE/MACE LESSONS LEARNED

- Low cost experiments happen

- Integration is an art, not a science

- PI should be responsible for payload mission success, ? intergrating center

- Crew can be vesitile contributor, if well prepared

- Investigator team must be prepared for mission operations, and their limitations

- Hardware shortcuts are penny-wise and pound foolish

- Scaling laws can be exploited to do small/low cost research experiments

- Flight experiments are fun, but take a significant fraction of a career