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NASA FUTURE MISSION NEEDS AND BENEFITS OF CONTROLS-STRUCTURES INTERACTION TECHNOLOGY

William L. Grantham

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Langley Research Center
Hampton, Virginia 23665-5225

ABSTRACT

This paper addresses two questions: 1) which future missions need Controls-Structures Interaction (CSI) technology for implementing large spacecraft in-orbit? 2) what specific benefits are to be derived if the technology is available? The answers to these questions have been used to help formulate and direct the CSI technology development program being jointly pursued at the Langley Research Center (LaRC), the Jet Propulsion Laboratory (JPL), and the Marshall Space Flight Center (MSFC). Many future NASA missions have common CSI technology needs which can best be developed in a broad-based, but focused, technology program to provide the greatest benefit to the largest number of users.

Three CSI benefit studies have been completed to date as part of an ongoing assessment process and have addressed missions requiring large antennas, missions requiring large optical systems, and missions requiring the use of closed-loop controlled, flexible, remote manipulator arms for in-space assembly. The benefit studies defined in this report are for missions with large antennas and flexible remote manipulator systems (RMS).

The CSI benefits study results for the Mission-To-Planet-Earth show that significantly larger antennas (80 meters) can be used if CSI technology is available as compared to much smaller (20 meters) antennas if it is not. Likewise, the science benefits study for the precipitation mapper on the Mission-To-Planet-Earth geostationary platform shows it is possible to meet science requirements of maximum measurable rain rate and resolution cell size using CSI technology to suppress antenna beam jitter whereas, without that control ability, the science requirements simply can not be met.

Results from the RMS benefit study, assuming use of CSI technology, show a decrease in the amount of RMS settling time by a factor of five, which would significantly speed up the Space Station Freedom assembly.

CONTENTS

1.0 INTRODUCTION

Conventional spacecraft design is accomplished by estimating size and mass of the spacecraft components and designing a structure sufficiently stiff to maintain the structure shape during operations; the control system is then designed to orient, guide and/or move the spacecraft to obtain the required performance. This traditional approach attempts to separate the lowest structural frequency and the control bandwidths, as shown in figure 1, so that the structure and control system do not interact. It is not uncommon, however, for solar panels or other long spacecraft appendages to have one or two modes in the control bandwidth so that notch filters have to be used to avoid their excitation by the control system. Performance is usually lost in the process. Looking to the future, these design issues are expected to become even more challenging.

Based on several august committee studies (references 1-6), future spacecraft are expected to get larger and more flexible with structural frequencies decreasing, in many cases, below 1 Hz, with many closely packed modes. Also, performance demands on the control system are expected to become more stringent and drive the control bandwidth to higher values into the same spectral region as the structural modes (shown at the bottom of figure 1). For a control system to operate in this environment without destructive excitation of the spacecraft or loss of performance requires a technology beyond that currently available.

Another challenging feature typical of large future spacecraft is the general increase of on-board disturbance levels and their bandwidths. This trend toward multi-sensor/multi-user spacecraft greatly improves coregistration of Earth located measurements from the many sensors and the cost per instrument is less when a common spacecraft (S/C) bus is used. Unfortunately, the additional disturbances (scanning mirrors, etc.) can excite unwanted structural resonances even if the control system does not.

In order to improve technology to meet the design demands for large spacecraft where there is spectral overlap of control/disturbance bandwidths and high density structural modes, a multi-center program was initiated to develop the CSI technology so it could be applied to spacecraft of the future (reference 7).

Specifically, the overall objective of the CSI program is to develop and validate the technology needed to design, verify, and operate spacecraft so that the structure and control systems interact beneficially to meet the requirements of 21st-century NASA missions. Program goals are listed below:

- Dynamic response amplitude reductions of 50 percent.
- Several orders of magnitude improvement in pointing precision.
- On-orbit performance prediction within 10 percent.
- Unified controls-structures model, analysis, and design.
- Flight system performance verification by analysis/ground test.

The CSI program long term goals are unusually specific for a technology development program. This has the advantage of helping target several specific future programs that could benefit from the new CSI technology, and it allows one to be definitive about what those benefits might be. Focusing the technology development in the direction of selected future missions also involves greater interaction between the technology developer and the technology user so that each is more sensitive to the needs of the other.

The CSI technology program objectives were developed using information from a number of available visionary documents and technology workshops. These documents define long range NASA mission options that can be accomplished if the appropriate technology is developed. Many of the future programs have common technology needs which can best be addressed in a broad-based CSI technology program, providing the greatest benefit to the largest number of users. The major documents and workshop information sources used in this study are listed below and in references 1 through 6.

WORKSHOPS

* Earth Science Geostationary Platform Technology Workshop. Langley Research Center CP 3040, September 21-22, 1988.
* In-Space Technology Experiments Workshop. December 6-9, 1988.
* Second Beamed Space Power Workshop. Langley Research Center, February 28-March 2, 1989.
* Global Change Technology Initiative (GCTI)
  * # 1--JPL March 1989
  * # 2--LaRC April 1989
  * # 3--GSFC May 1989
* Workshop on Technologies for Space Optical Interferometry, April 1989 & 1990.
* Workshop on the Next Generation Space Telescope, September 1989.

2.0 FUTURE MISSIONS NEEDING CSI TECHNOLOGY

Future missions with a potential for benefiting from CSI technology have been divided into four main categories listed in figure 2. Lead center responsibility for each category is shown in parentheses. Specific features of each mission concept can be found in the reference literature. All of them have large flexible spacecraft structures and high bandwidth control systems. Some of them have been selected as focus missions. The selection was based on maturity in mission concept and need. The more CSI features in common with other future missions multiplies the benefit of the technology. The selected focus missions also are perceived to have high priority in terms of national need and challenging CSI features relative to current technology.

Many of the spacecraft geometric features taken from these mission categories have been included in the analytical models and ground test models selected by LaRC, JPL, and MSFC. Specific model features selected for the CSI Program are discussed in references 8-11.

The focus of the LaRC part of the multi-center CSI program emphasizes technology needs for large space antennas on flexible platforms carrying many separately controlled payloads and appendages. Examples of these type missions are the Mission-to-Planet-Earth geostationary spacecraft and the growth configurations of Evolutionary Space Station Freedom.

The specific CSI features of interest for Mission-To-Planet-Earth geostationary spacecraft are the large platform used to mount multiple sensors (many of which cause significant disturbances due to scanning mirrors, etc.), the flexible articulating antennas, and the sensor pointing requirements that exceed current state of the art.

The JPL task focuses on the development of CSI design technology for micro-precision controlled structures. This technology is needed for large optical systems such as large (20 to 100m) optical interferometers and for some high surface accuracy (micron level) microwave antennas (reference 11).

The astrophysics systems category being addressed by MSFC includes missions such as the X-Ray pinhole occulter flight experiment now under study. That flight experiment would provide science as well as serve as a CSI technology experiment on Space Shuttle then later on Space Station Freedom. MSFC is developing the ground test facilities and definition studies for technology flight experiments in this category of missions (reference 12).

Studies are currently underway to address CSI issues associated with specific features of Space Station Freedom listed, on figure 2, as will be described later in the report.

3.0 LARGE SPACE ANTENNA MISSION NEEDS

Many future missions need antennas larger than the 9-meter antenna flown on ATS-6 in 1973. CSI technology will be required to maintain their precise shape and beam pointing stability. This is because larger antennas will be more flexible and more subject to distortion, and because they must work at shorter wavelengths requiring much higher quality control on antenna dimensions than ever before.

The six specific programs listed in figure 3 must use large space antennas (LSA) in order to meet the mission requirements. Antenna diameters needed by each mission (shown in parentheses) are taken from white papers and workshops. In some cases, the large antennas must be scanned; others must be attached to a large platform with many other sensors having disturbance generating scanning mirrors, etc. This, of course, makes the CSI design even more challenging and the potential of CSI technology benefits still greater.

The first focus mission selected by LaRC for a detailed look at technology needs and related CSI benefits (assuming successful development of CSI technology) is the Mission-To-Planet-Earth Geostationary Platform (Geoplat).

4.0 ELEMENTS OF MISSION-TO-PLANET-EARTH

The centerpiece of the U.S. contribution to the international Mission-To-Planet-Earth Program is the Earth Observing System (EOS) polar orbiter with later plans to add five geostationary spacecraft. New-start for the low Earth orbiter EOS-A was in F.Y. 1991 and does not require new technology to meet its measurement requirements. The geostationary orbiting spacecraft, however, require very large scanning microwave radiometer antennas for making precipitation maps of the Earth every 30 minutes, and have very stringent infrared/visible band sensor pointing requirements. To satisfy these needs technology development will be required. New-start of the geostationary spacecraft part of this program is not expected until F.Y. 1995 which allows enough time to develop the needed technology and establish its credibility with a proof-of-concept flight experiment.

Several studies have been completed to characterize different design concepts for the Geoplat. For example, a Geoplat Phase-A study by MSFC (reference 13) includes a small antenna (4.4 meters) for precipitation mapping because current technology will not allow anything larger that will fit within the vehicle launch envelope. The 4.4-meter antenna size, although big enough for some science requirements, is more than a factor of 10 too small to meet the precipitation requirements as will be shown later in this report.

Larger antennas for Geoplat (20 meters) have been considered in a Goddard Space Flight Center study (reference 14) which assumes assembly in orbit, but the serious question of antenna beam jitter for the larger antennas remains. Studies have been conducted at LaRC specifically regarding the three-dimensional dynamics of a large spacecraft, such as Geoplat, that show prohibitive pointing jitter for antennas larger than 20 meters unless CSI technology is employed (references 15 & 16). Details of this study are discussed next.

5.0 MISSION BENEFITS FROM CSI TECHNOLOGY

The first focus mission benefit study was for the Mission-to-Planet-Earth Geoplatform. The question to be answered was: what specific advantages are there in applying CSI technology in the design of that spacecraft? This question can be answered by defining differences in the mission performance capability using both the traditional and CSI approach. The antenna pointing jitter performance improvement was chosen as the parameter for study. Another CSI benefit quantified in this study is the science benefit of being able to use larger antennas with the microwave and millimeter wave precipitation mapping sensors.

5.1 LARGE SPACE ANTENNA PERFORMANCE IMPROVEMENT

In order to provide the needed precipitation maps of the Earth every 30 minutes for Mission-To-Planet-Earth, precision pointing and beam scanning are necessary for the large microwave radiometer antennas shown on each end of the geostationary platform (figure 4). Since this beam scanning will most likely be accomplished mechanically by moving some parts of the antenna, this and other spacecraft disturbances will cause feed-mast flexure and antenna distortion resulting in beam pointing jitter. Jitter up to 10 percent of the resolution cell size is allowed without seriously degrading the quality of the precipitation map developed by the beam raster scan. As the figure shows for the 20 GHz microwave antenna, beam jitter requirement becomes more stringent as LSA diameter increases since beam width varies inversely with antenna diameter. The 15 meter antenna jitter results were scaled to other antenna diameters using scaling laws presented in reference 15.

The two performance curves indicate expected pointing capability, with and without the use of Control-Structures Interaction technology, for the LaRC/Ford Aerospace model (reference 16). Without CSI technology, the beam jitter is acceptable only for antennas below 20 meters in diameter. In contrast to that limit, antennas up to 80 meters in diameter could be used while still meeting a 10-percent pointing jitter requirement if CSI technology is employed.

The technology benefit, for this example case study, is that significantly larger antennas can be used with improved performance for future missions if CSI technology can be developed to provide the two orders of magnitude active control and increased passive damping from 0.5 percent to 5 percent as assumed here. This is a design goal of the CSI program. Currently demonstrated active control for ground-based experiments provides only about one order of magnitude in pointing improvement.

Once developed, the CSI technology will enable a number of important missions, such as the Mission-To-Planet-Earth, and assure improved performance capability for similar large space antenna missions such as the Very Long Baseline Interferometer (VLBI) for radio astronomy, advanced communication systems, and aircraft surveillance systems.

5.2 SCIENCE BENEFITS FROM CSI TECHNOLOGY

Although it is clear that CSI technology allows larger microwave and millimeter wave antennas for remote sensing, the key question is: how does that improve science for the Mission-To-Planet-Earth Program? The answer is, in two ways. First, the use of larger antennas allows superior spatial resolution to better match the correlation length of rain cells (typically 10 km or less). This avoids partially filled resolution cells which would result in measurement errors. Resolution cell size is proportional to the ratio of spacecraft altitude to the product of electromagnetic frequency (f) and antenna diameter (D), as shown in figure 5. If it were not for the fact that choice of electromagnetic frequency also determines the maximum measurable rain rate, the antenna diameter could be kept small and still meet the resolution cell size requirements simply by using ultra high frequencies (millimeter wavelength band). The microwave radiometer sensitivity to different rain rates is shown in figure 6.

Second, the use of larger antennas allows, with CSI technology, rain rate measurements over the full dynamic range by using both millimeter and microwave frequencies rather than being restricted to light rain measurements (<10 mm/hr.) with small millimeter wave antennas. The approximate $1/f^2$ radiometer brightness temperature dependence, shown as an example in figure 6, indicates that a 20 GHz radiometer saturates at rain rates above 10 mm/hr. This saturation limit was demonstrated by the 1973 Electrically Scanning Microwave Radiometer (ESMR) in low Earth-orbit (reference 17). In order to measure the higher rain rates, a lower microwave frequency must be used. Six GHz is shown as an example. Therefore, for a required resolution cell size of 20 km and a geostationary orbit altitude of 35,000 km, the antenna diameter must be about 80 meters for 6 GHz. Only through the use of the lower frequency microwaves can the moderate and heavy rain rates be measured, thus, providing a comprehensive data set.

The percentages shown on the lower abscissa scale of figure 6 are based on rain statistics derived from the tropics (reference 18) and do not necessarily apply to global statistics which are currently unknown.

Translating the resolution cell size and microwave frequency requirements into specific precipitation requirements is shown on figure 7. This science benefits chart shows specifically how CSI technology improves resolution and rain rate measurements as an example case study. Without beam jitter control on the antenna, the precipitation measurements would be restricted to the region on the left of the 20-meter antenna diameter curve labeled "Without CSI Control". This severely limits the maximum measurable rain rate and the resolution cell size. In contrast to that limit, the use of CSI control with a beam jitter controlled 80-meter antenna provides data that are almost completely within the science measurement requirements zone.

For comparison, the capability of several previous and current low Earth orbit satellite radiometers are shown which have been used to provide rain maps of the Earth. It is clear that large antennas will have to be used for GeoPlat and that CSI technology will be needed to meet the science requirements. There is currently underway a considerable effort to develop millimeter wave radiometry to infer the high rain rates. If successful, this measurement method would, when combined with CSI technology, allow resolution cell sizes to approach ideal science values (1 km) rather than be limited to the 20 km "acceptable" values possible at 6 GHz.

6.0 BENEFITS OF CSI TECHNOLOGY TO SPACE STATION ASSEMBLY BY FLEXIBLE ROBOTIC MANIPULATOR SYSTEMS

Based on experiences from many previous Shuttle flights, the oscillations of the RMS/payload system have been found to add time to payload deployment, retrieval, and maneuvering. For example, the crew must wait for the oscillations to damp sufficiently to determine the results of the last input. This insures that the next input is not phased so as to enhance the oscillation. A robotic system with a CSI controller might significantly reduce settling time during Freedom assembly and later for Moon and Mars vehicles assembly.

To quantify the CSI settle-time reduction, a benefits study was conducted with McDonnell Douglas for a CSI controller applied to the flexible Space Shuttle RMS for the assembly of Space Station Freedom (reference 19). The CSI case was compared with assembly times using the present Space Shuttle RMS. The comparison was for baseline assembly sequence #20/13. The number designation indicates 20 flights are required to accomplish complete assembly (for the first 13 flights Freedom is unmanned). This was the most detailed assembly sequence defined at the time the study began. There were 101 items in the 20 flights and RMS settling time was estimated as a function of the payloads for 8 different weight classes. In the study it was found that 65 percent of the RMS settling times--without CSI technology--are predominantly related to payloads in 2 weight classes (3000 lbs ± 2000 lbs and 7500 lbs ± 2500 lbs).

A typical RMS time response is shown at the top right of figure 8. For this study, settling time was defined as the amount of time required for the oscillations at the tip of the RMS to reduce to 2 inches (peak-to-peak). The RMS settling time without the CSI controller was computed for each of the 20 missions relative to the total RMS activity time (see bottom left of figure 8). Following that, the potential settling time reductions for a CSI controller with different assumed damping factor improvements was calculated, as is shown on the right hand bottom inset of figure 8. Significant time savings can be realized with even modest CSI improvement in arm damping.

7.0 CURRENT BENEFIT STUDIES UNDERWAY

Having completed the benefit studies presented in this report, the next focus mission has been selected and benefit study initiated to determine if CSI technology could improve user accommodations on the Evolutionary Space Station Freedom. Early studies have already shown that some baseline activities on Freedom, such as crew treadmill and RMS activities, are most likely to require schedule work-arounds to avoid conflicts with user requirements for microgravity and precision pointing. In the benefits study, user requirements and related disturbances will be defined and used as input to a Finite Element Model of Freedom (Extended Operating Capability -XOC Configuration) developed at LaRC (reference 20). The study will determine the extent of environment improvement possible using CSI technology.

It is clear that the CSI technologist must have a good understanding of what specific types of environmental improvements the researcher needs in order to provide design countermeasures. Just as in the Geoplat case where the physics of the precipitation measurement played an important part in choice of electromagnetic frequency (and thus antenna diameter), it is important that the physics of preferred microgravity environment be understood in order to design countermeasures to improve it. Figure 9 shows an example of the degree of concern the microgravity researchers have with different types of environmental disturbances and several types of material processing (references 20 & 21).

8.0 SUMMARY

Several future mission categories have been identified that need Controls-Structures Interaction (CSI) technology for implementing large spacecraft in-orbit. Three specific focus missions selected in this study have been used to help formulate and direct the CSI technology development program being pursued at LaRC, JPL, and MSFC.

Three CSI benefit studies have been completed to date as part of an ongoing assessment process and have addressed missions requiring large antennas, missions requiring large optical systems, and settle-time reduction using flexible remote manipulator arms. The optics missions benefits are covered in a separate publication.

The benefits study results for the Mission-To-Planet-Earth show that science returns can be significantly enhanced with larger antennas (80 meters) if CSI technology is available as compared to a much smaller (20 meters) antenna limit without CSI technology.

Results from the benefit study assuming use of CSI technology to speed up Freedom assembly shows a decrease of five in the amount of settling time for the Shuttle RMS if the damping factor is improved by a factor of three. Damping factor improvements in this range are considered achievable with current CSI technology.

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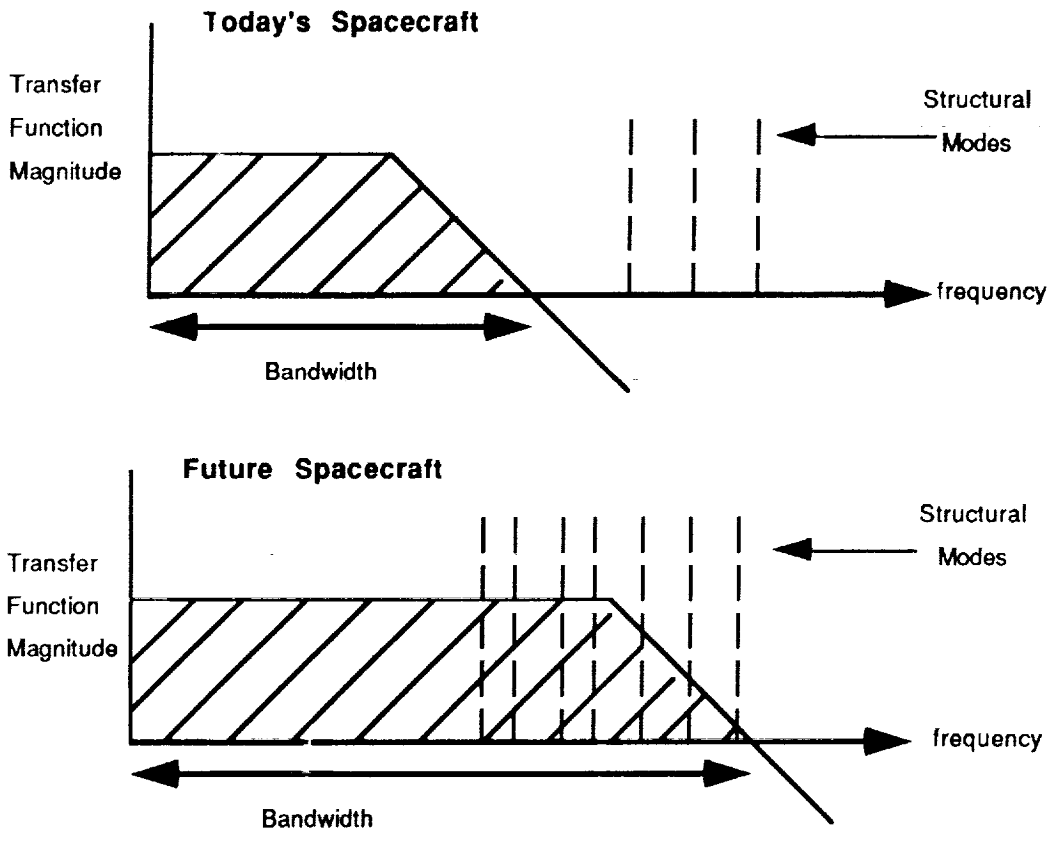


Figure 1. - Controls-Structures Interaction.

- LARGE SPACE ANTENNAS (LaRC)
- LARGE OPTICAL SYSTEMS (JPL)
- ASTROPHYSICS SYSTEMS (MSFC)
- SPACE STATION SYSTEMS
  * Flexible RMS
  * Attached Payloads
  * Microgravity Facilities

Figure 2. - Mission Categories.

- MISSION-TO-PLANET-EARTH
  * Leo
  * Geo (4.4 m --->200 m)

- DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP) BLOCK-6 (6 m)

- FAA AIRCRAFT SURVEILLANCE / COMM (20 m)

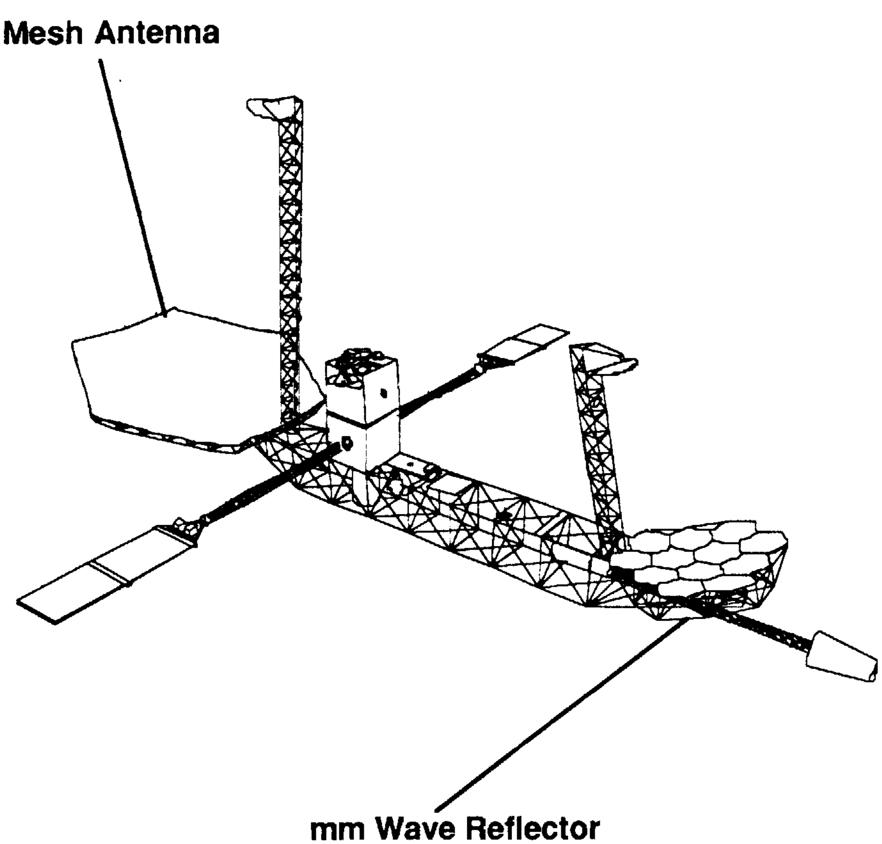
- RADIO ASTRONOMY------VLBI (20 m)

- COMMUNICATION SATELLITES (15 --> 55 m)

- IN-SPACE POWER TRANSFER (1000 m)

Figure 3. - Large Space Antenna Related Missions.

"Mission to Planet Earth" Platform



Pointing Performance

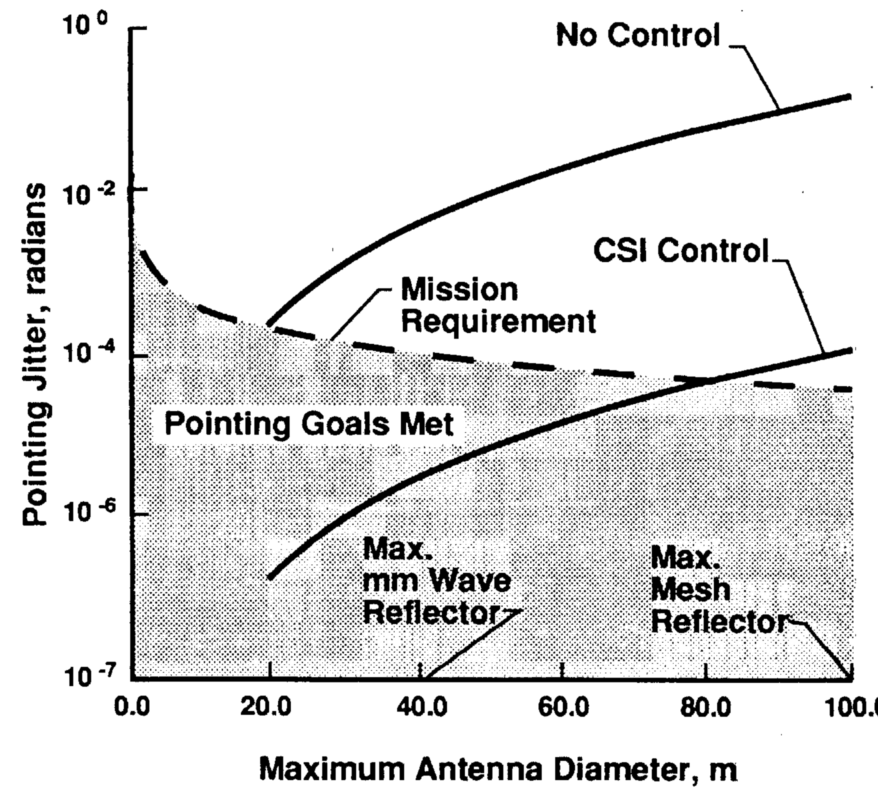


Figure 4. - CSI Performance Improvement.

SCIENCE PARAMETERS	ANTENNA PARAMETERS
Resolution Cell Size	$\propto$ (Altitude) / (f x D)
Rain Fall Rate	Max. Meas. Rain Rate $\propto 1 / f^2$

Figure 5. - Conversion of Large Space Antenna Benefits Into Science Benefits for Geoplat.

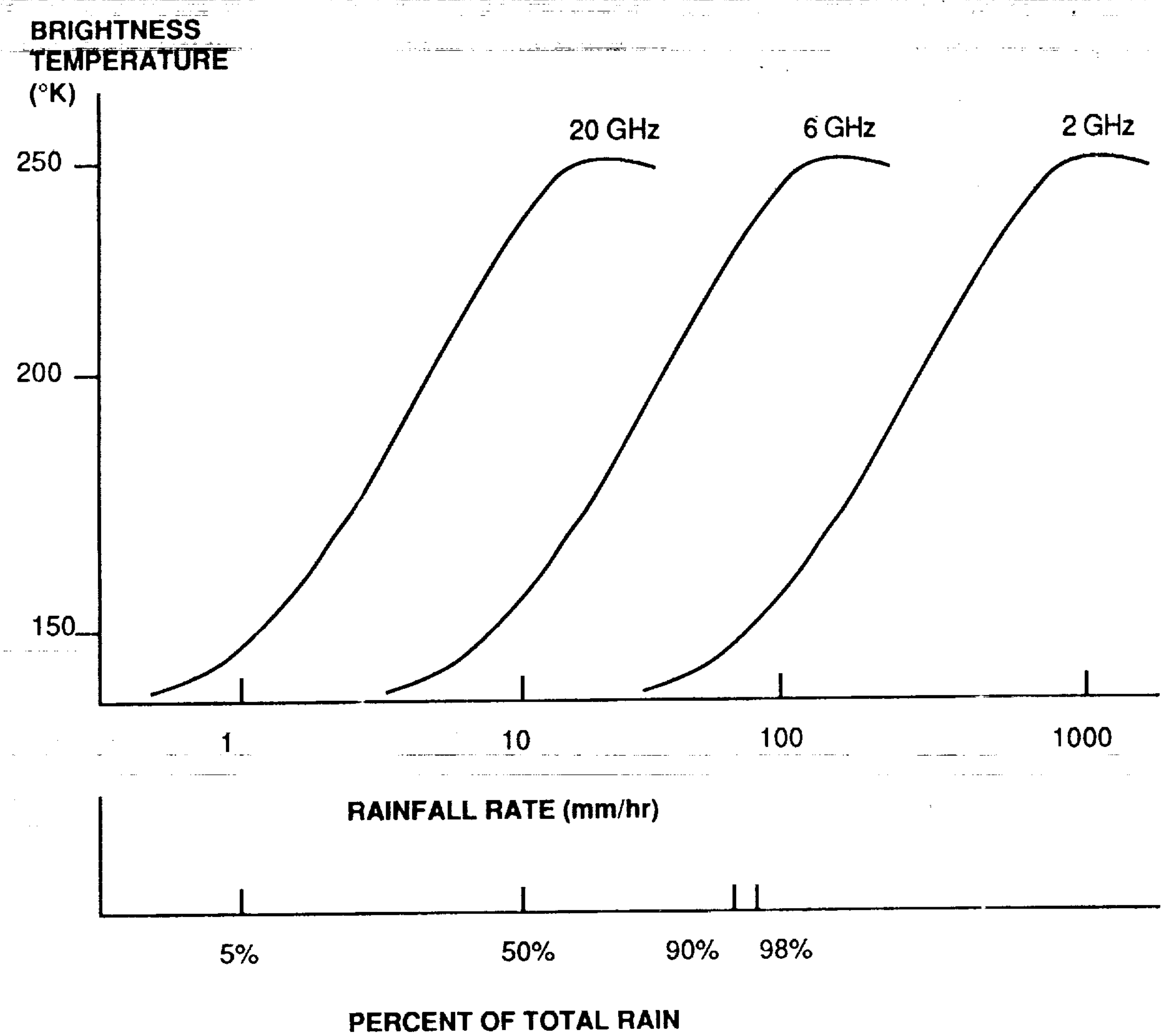


Figure 6. - Radiometer Sensitivity.

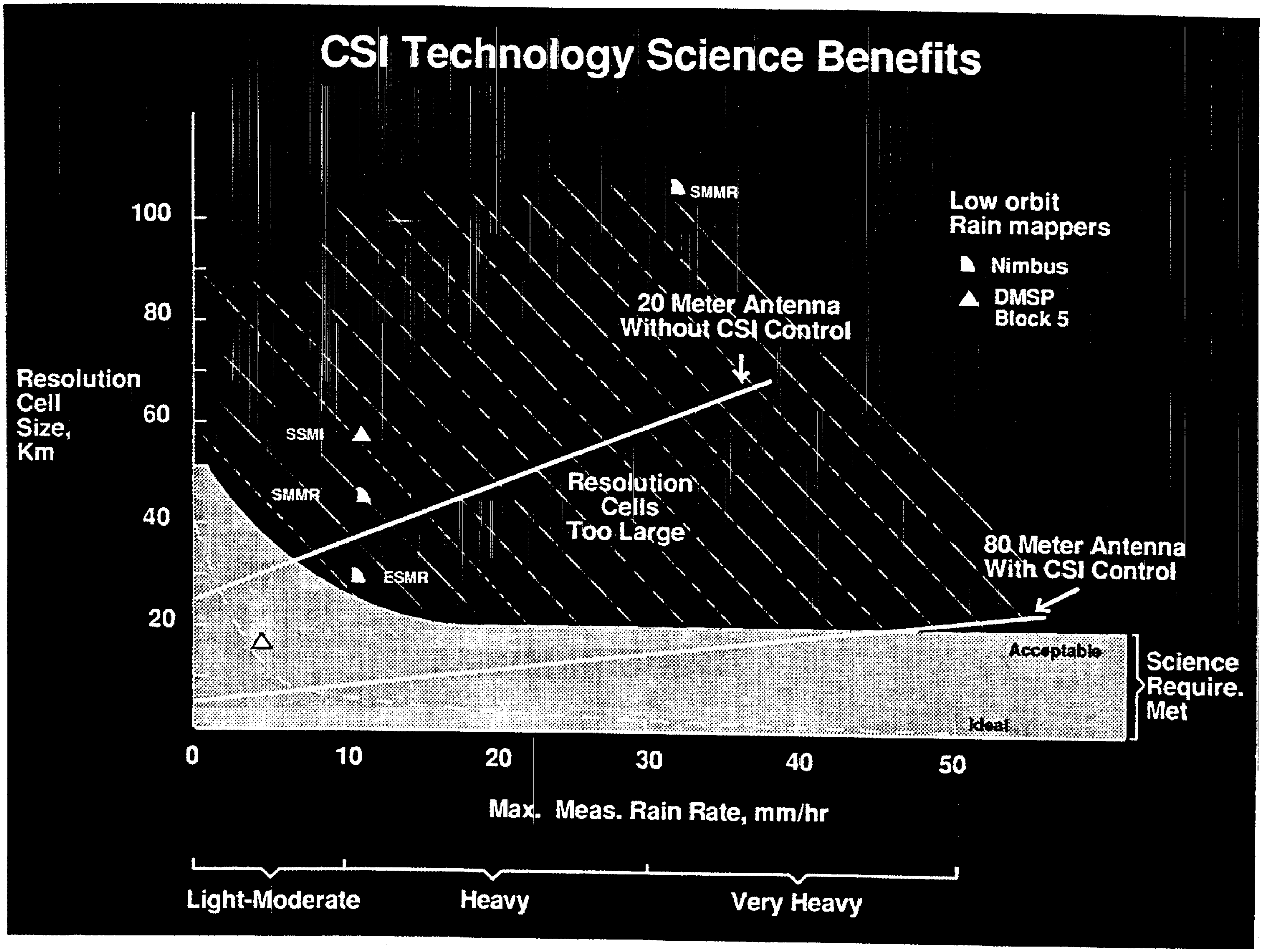


Figure 7. - CSI Technology Science Benefits.

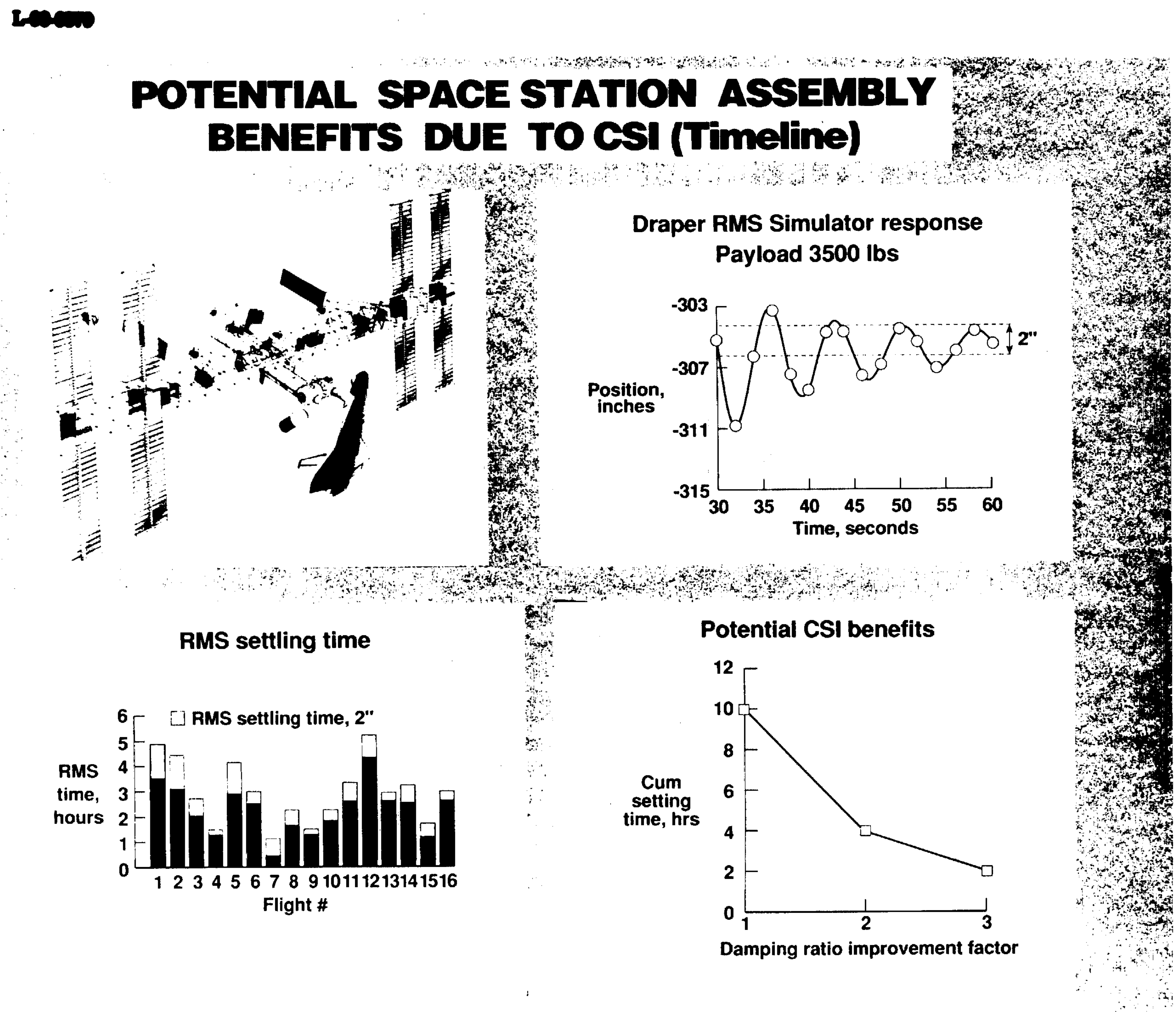


FIGURE 8 RMS BENEFITS

ENVIRONMENTAL EFFECTS ON MATERIAL PROCESSING

Envir. Example \ Type Exp.	Contained Solidification	Quasi-Containerless Solidification	Containerless Experiments	Fluid Experiments
Low-Level Steady Accelerations	Possibly Serious	Possibly Serious	Unimportant	Possibly Serious
Crew Soar	Relatively Unimportant	Possibly Serious	Possibly Serious	Relatively Unimportant
RCS Firing	Possibly Serious	Possibly Serious	Relatively Unimportant	Possibly Serious
Rotation-Induced Flows	Should be Avoided	Should be Avoided	Unimportant	Should be Avoided

Figure 9. - Environmental Effects on Material Processing.

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15. Supplementary Notes

16. Abstract

This paper addresses two questions: 1) which future missions need Controls-Structures Interaction (CSI) technology for implementing large spacecraft on-orbit? and 2) what specific benefits are to be derived if the technology is available? The answers to these questions have been used to help formulate and direct the CSI technology development program being jointly pursued at LaRC, JPL, and MSFC. Many future NASA missions have common CSI technology needs which can best be developed in a broad-based, but focused, technology program to provide the greatest benefit to the largest number of users.

Three CSI benefit studies have been completed to date as part of an ongoing assessment process: 1) missions requiring large antennas; 2) missions requiring large optical systems; and 3) missions requiring the use of closed-loop controlled, flexible, remote manipulator systems (RMS) for in-space assembly. The large antenna and flexible RMS mission benefits are the subjects of this report.

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