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SUPPORTING DEEP-SPACE-NETWORK RESEARCH AND DEVELOPMENT WITH A STUDENT-DESIGNED SATELLITE

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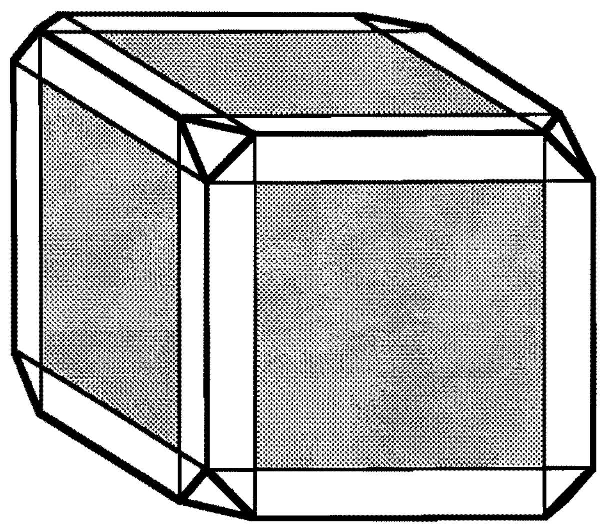

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SURFSAT: SUPPORTING DEEP-SPACE-NETWORK RESEARCH AND DEVELOPMENT WITH A STUDENT-DESIGNED SMALL SATELLITE

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SURFSAT is a small satellite designed primarily by students at the California Institute of Technology under Caltech's Summer Undergraduate Research Fellowship (SURF) program and is sponsored by the Telecommunications and Data Acquisition Office at JPL, the research and development arm for the Deep Space Network (DSN). The project was initiated in the summer of 1987 and has involved several dozen undergraduate students.

SURFSAT is designed to radiate at either the milliwatt or microwatt level in four bands: S-band (2.29 GHz), X-band (8.45 GHz), K_u-band (15.33 GHz) and K_a-band (32 GHz). The signals will be received by a new 34-meter DSN research antenna at Goldstone, California. Performance of the new K_a-band link will be analyzed and compared to the performance of the more standard X-band link. The S-band and K_u-band signals will be used to support DSN spacecraft acquisition tests and training. Other experiment objectives have also been identified, including spacecraft position and orbit determination demonstrations utilizing ground-based connected-element interferometers. It will also carry an optical beacon to demonstrate the possibility of communicating at infra-red wavelengths. The basic SURFSAT satellite is a solar powered cube, 12 inches on each side, that will tumble through space. Attitude stabilization is not required, and the satellites will not have a propulsion subsystem or batteries. Signals are to be radiated in all directions. Redundant command receivers will enable transmit modes of one milliwatt, one microwatt, and OFF. At least two SURFSATs are scheduled for launch as secondary payloads on a Delta rocket in May 1994; the primary payload for this mission is LAGEOS III.

Introduction

This paper will discuss a student project sponsored by the Jet Propulsion Laboratory called the Summer Undergraduate Research Fellowship Satellite (SURFSAT). It will describe the history and rationale behind the project, its goals and accomplishments to date.

Historical Perspective

The exploration of the Solar System by NASA has experienced a progressive expansion in the capabilities of its unmanned spacecraft. It started with planetary flybys and this phase of early reconnaissance ended with the grand odysseys of the late Pioneers and Voyagers. NASA's current generation of unmanned explorers are designed to carry out experimental observations for periods measured in years as long-duration orbiters. The Venus orbiters and the Mars-Viking missions were some of the first examples of this new breed. Likewise, missions currently enroute or under construction (such as Galileo and Cassini) embrace the objectives of this latest phase in exploration. The future will herald missions of heretofore unknown complexity: rendezvous, landing, roving, and return. Concurrently, NASA's ability to communicate with and support its spacecraft via the Deep Space Network (DSN) has grown to accommodate these changes.

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The past three decades of deep space telecommunications can be characterized by the progressively higher operating frequencies used. The DSN started using L-band (960 MHz) in 1960 before switching to S-band (2.3 GHz) in the mid-1960's. It added an X-band (8.4 GHz) capability in the mid-1970's.

The frequencies used for deep space communication can be found at certain windows through which microwave transmissions can pass through the Earth's atmosphere with very low loss and little noise. As we can readily see from Figures 1 and 2, K_a-band (32 GHz) was selected as the next operating frequency for the DSN because it is the last allocation in the microwave spectrum where a ground-based antenna's system temperature is low enough to allow good reception of weak signals from deep space (Reference 1).

By progressively operating at higher frequencies, the DSN can take advantage of the favorable increase in link capacity provided by such a shift without having to resort to a huge increase in transmitter power output or antenna diameter. By switching from L-band to S-band to X-band, the DSN's telecommunications capability was improved by a factor of 77 (18.9 dB) for the same antenna sizes, transmitter power and receiver sensitivity.

This occurs because a narrower beam is achieved at higher frequencies for a given antenna size. This results in a higher power density at the receiving location and hence, more power at the receiver. In fact, the capacity of a link established between two well-aimed high-gain antennas scales, to a first order, as the square of the operating frequency. Therefore, an improvement factor of 14.5 (11.6 dB) can be achieved by going to K_a-band from X-band (Reference 1).

The actual realizable gain in performance will not be as great. It is reduced by losses in the Earth's atmosphere and the limiting tolerances of the various components in the link. So, the actual gain may be 6 to 10 dB (depending on the weather) instead of the figure quoted above. Even so, the impact of such a gain can be immense. Figure 3 shows that even if only a 6 dB increase was realized, first, that a very large array of X-band antennas has the same reception capability (G/T or Gain vs. System Temperature) as one 70-meter antenna at K_a-band and second, that a 70-meter X-band antenna has the same reception capability as one 34-meter antenna at K_a-band. Dickinson presents a more detailed comparison of the X- and K_a-band telemetry links in Reference 2.

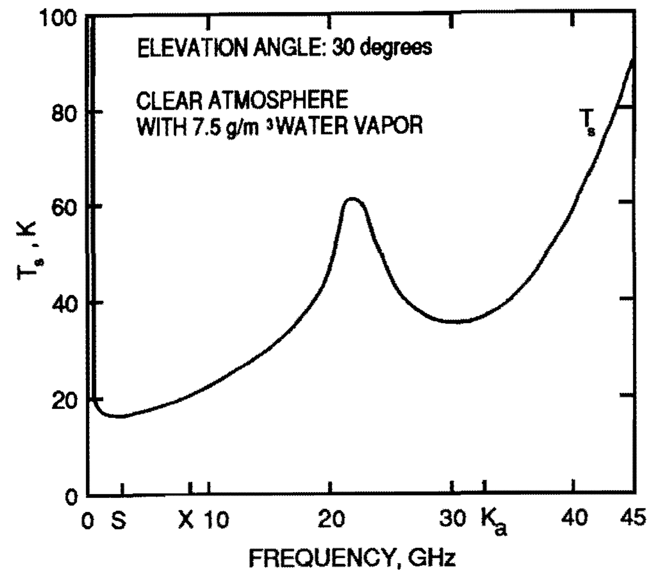


Figure 1. Projected DSN 70-meter antenna system temperature

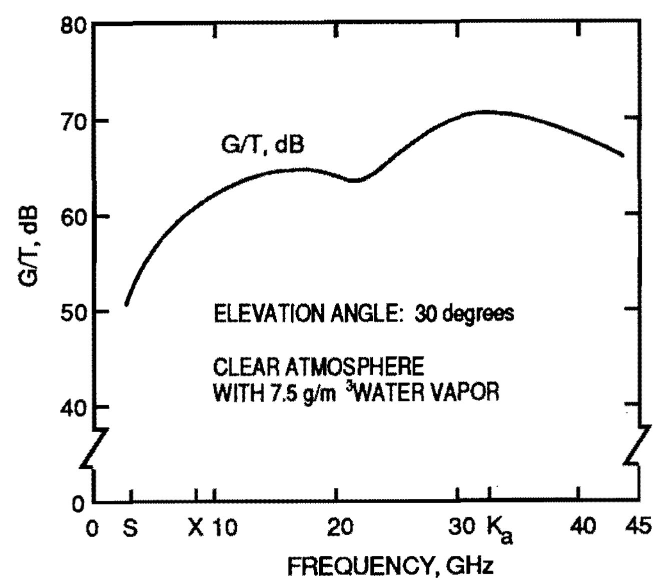


Figure 2. Projected DSN 70-meter antenna system Gain vs. System Temperature (G/T)

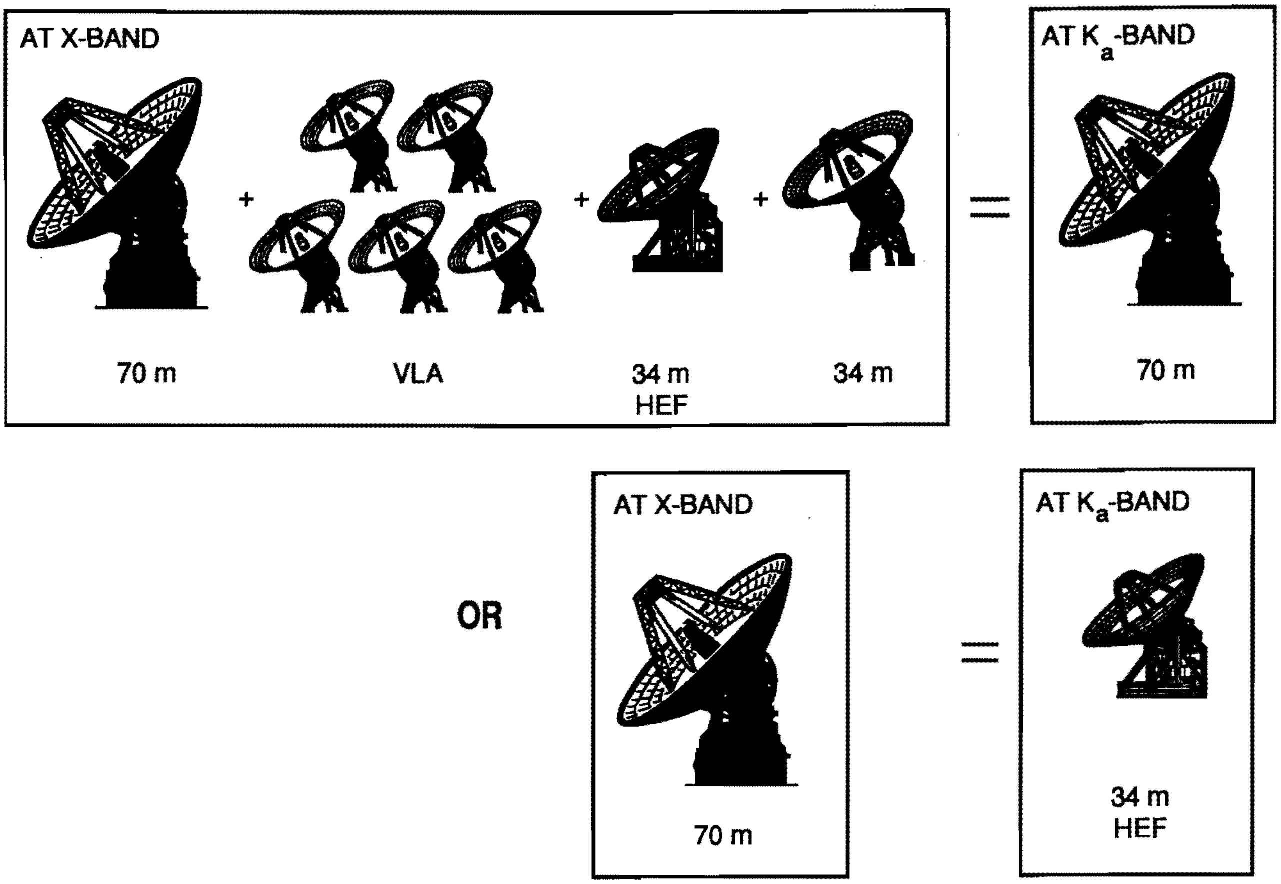


Figure 3. The X- and K_a-band G/T Equivalences

While K_a-band was accepted as the next logical frequency to use, conversion of deep space communication to this frequency will not start until the technology required to use it has been developed and demonstrated to provide the benefits anticipated and modelled. The verification process will take several steps, among which will be the continued measurement of weather effects at K_a-band at all three DSN complexes (U.S., Australia and Spain) to refine the weather model essential to projections of deep space link performance; the development of a DSN R&D ground antenna to verify the benefits of various approaches to be used to upgrade the existing antennas to good efficiency at K_a-band; and augmentation of planned deep space spacecraft with K_a-band beacons to obtain accurate relative performance measurements in both K_a-band and X-band during simultaneous reception.

The Satellite

Early in 1987, a group of JPL engineers envisioned a small Earth-orbiting satellite that could be used for tests of the K_a-band frequency allocation. The spacecraft, SURFSAT, would orbit at an altitude above 5000 km and radiate very weak microwatt level signals, thereby simulating a deep space vehicle such as Voyager or Galileo. It would be launched in the Spring of 1994 and operate in conjunction with Deep Space Station 13 (DSS-13), the recently completed DSN R&D ground antenna in Goldstone, California.

This group, composed of Robert Clauss, Rex Ridenoure and Doctors Edward Posner and Joel Smith, also proposed that the project involving the study, design, and construction of the relatively simple spacecraft be carried out under the auspices of the California Institute of Technology's Summer Undergraduate

Research Fellowship (SURF) program. Under this program, successive teams of college students would work for 10 weeks during the summer on specific tasks related to the satellite and its mission with technical assistance provided by volunteer specialists employed at JPL. The SURFSAT effort is funded and managed by the Telecommunications and Data Acquisition (TDA) Office at JPL, the research and development arm of the DSN. In this manner, JPL would provide students with the opportunity to gain real-world technical experience in the design and construction of a satellite in return for an inexpensive satellite useful to its R&D program.

The satellite, would carry the following payload:

a) Two redundant narrow-band command receivers which could only be reached by a 20 kilowatt, 34-meter ground-based antenna operating at 7.191 GHz (X-band). They in turn would enable transmit modes of 1 milliwatt, 1 microwatt and OFF.
b) An X-band transmitter operating at 8.451 GHz.
c) A K_a-band transmitter operating at 31.9096 GHz. (Reference 3)

SURFSAT would serve the DSN as a tool for use during the verification process for the gathering of data on the relative performances of X-band and K_a-band under various weather conditions using different signal intensities. This data would allow JPL to make a quantitative analysis of the benefits to be gained by the upgrade to K_a-band. It would also, amongst other things, provide a target for the DSN to carry out acquisition testing and training. A satellite of this type would be desirable because of its relative cheapness and greater flexibility compared to the proposed experimental beacons to be carried by future deep space probes.

The project was initiated in the summer of 1987 when the first group of SURF students was introduced to small satellite and Get-Away-Special technology by the staff at Utah State University and Globesat, Inc., in Logan, Utah. Feasibility studies investigating the concept were completed in the summer of 1989. The development of critical subsystems followed immediately afterwards. The summer of 1990 saw the completion of the preliminary designs for various critical subsystems, including the X- and K_a-band transmitters and the command receiver.

Meanwhile, other students have made significant progress working on such issues as mission planning, structural design and thermal behavior, power distribution and the selection of transmitter components. So far, students from Caltech, Occidental College, Arizona State University and U.C. Berkeley have participated in this SURF project. JPL further contributed to the effort by providing the Spectrum Planning Subcommittee of the National Telecommunications and Information Administration (NTIA) with the required documentation for the Stage 2 system review (Reference 4). The system review details the SURFSAT satellite and its mission and officially requests the NTIA for permission to operate in the frequency bands planned for SURFSAT.

Each student, in their assigned tasks of designing a particular component of the spacecraft, faced a number of real-world challenges. Chief among them was the lack of fixed and detailed design parameters. Instead, parameters such as size, weight and cost were left to the student to set after having examined the technology available. Matters were complicated further by the fluidity of the SURFSAT mission.

Between June 1990 and May 1991, the satellite's mission was expanded. In addition to the mission goals stated above, it was given the further objectives of providing an S-band beacon for the DSN to use for acquisition tests and training and connected-element interferometry demonstrations as well as serving as an inexpensive, low-risk platform for the testing of new telecommunications concepts. Thus, an S-band transmitter (operating at 2.2895 GHz) and a K_u-band transponder (with an uplink at 15.329 GHz and a downlink at 14.150 GHz) have been added to the payload with the further possible addition of an optical link demonstration experiment operating at a wavelength of roughly 860 nm. The functional block diagram for the spacecraft and its new science payload can be seen in Figure 4.

The K_u-band transponder will receive a continuous wave signal from earth and coherently transmit it back on a different frequency. It will be used for precise Doppler measurement experiments in preparation for the

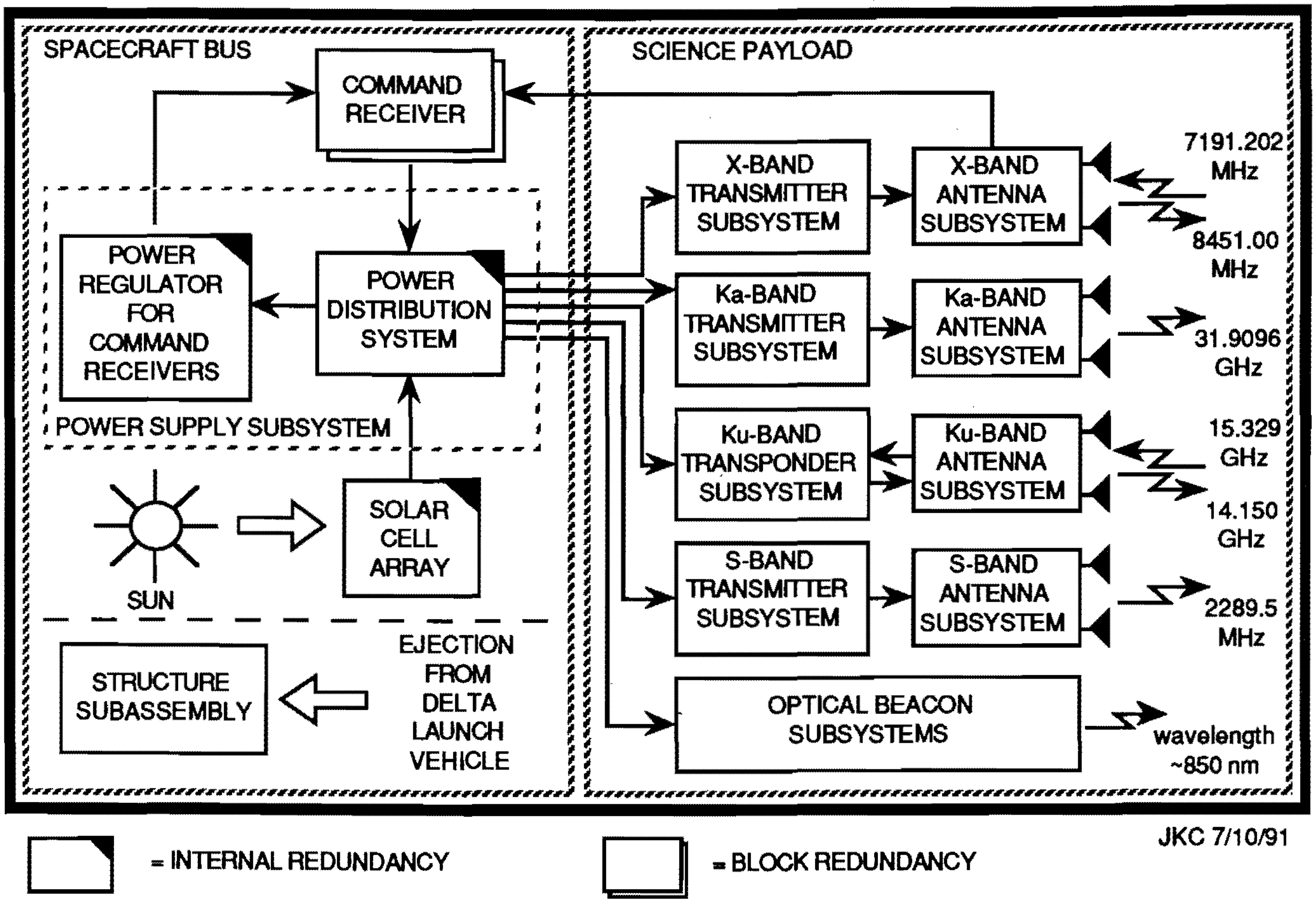


Figure 4. SURFSAT Functional Block Diagram

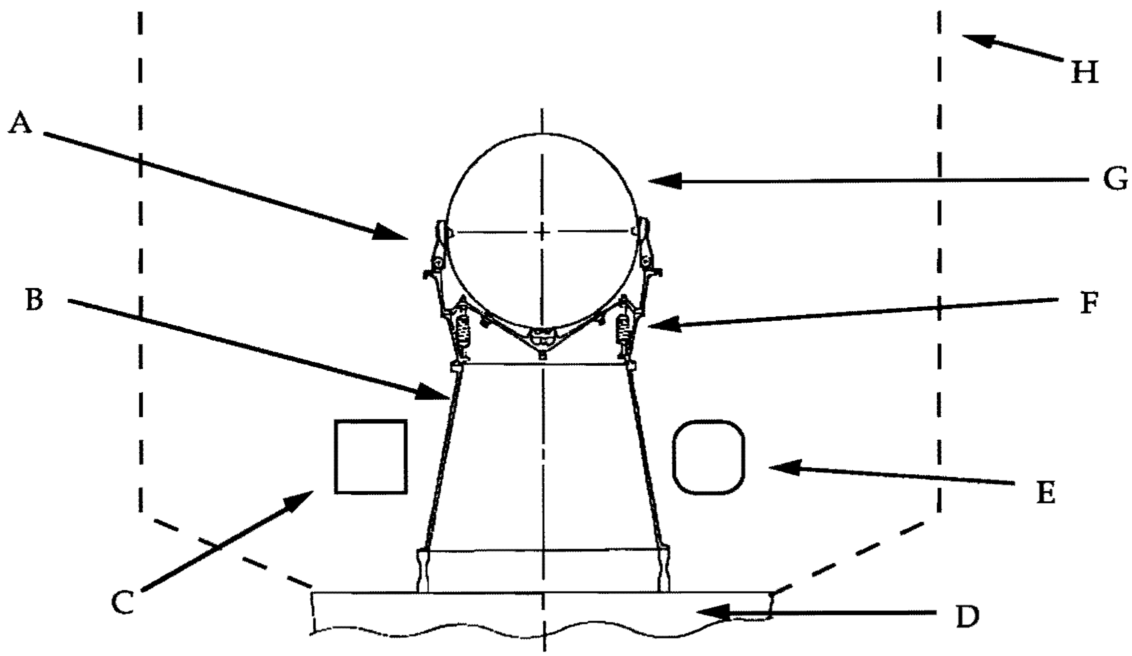
DSN's support of the Soviet RADIOASTRON and Japanese VSOP orbiting Very Long Base Interferometry (VLBI) missions. They require continuous sets of such measurements for a successful mission. The optical link experiment, consisting of two diode lasers and some fiber-optics, will be part of a set of demonstrations aimed at verifying the use of the infra-red spectrum for communication and telemetry purposes.

Development of the K_u-band transponder and a feasibility study investigating the possibility of adding the optical link demonstration experiment were initiated in the summer of 1991. It should still be noted, however, that despite these later payload additions, the *primary* payload and mission still remains the same, that is, experimental observations in the X- and K_a-band frequency allocations. The other payloads will only be launched if they are ready before the Winter of 1993.

These "conditional" payloads were added because SURFSAT's launch date had been put back one-and-a-half years. SURFSAT was to have been launched in October of 1992 as a free-flying, secondary payload aboard the DELTA II vehicle placing the third Laser Geodynamics Satellite (LAGEOS III) in orbit. Since the autumn of 1990, LAGEOS III's launch has been rescheduled to the May of 1994.

But this extra time will not only be spent on developing the new assigned SURFSAT science payloads, it will also be used to finish developing various subsystems such as the power distribution system (PDS) and the satellite's structure. In addition, the teams will also attempt to construct a second, duplicate SURFSAT to launch alongside the first. The launch configuration proposed by the LAGEOS III and DELTA II project offices calls for SURFSAT to be mounted off-axis, inducing a requirement for ballast aboard the launch vehicle if only one SURFSAT spacecraft should be launched (see Figure 5). To reduce waste (by launching useful hardware instead of useless ballast) and increase the chances of mission success with a greater margin of redundancy, a second SURFSAT spacecraft would be desirable.

However, while the decision to launch as a "free-flyer" means significantly reduced project costs, it also involves accepting certain restrictions which would not otherwise exist. The primary payload is a solid brass sphere covered with corner reflectors which NASA's Goddard Space Flight Center will use to measure Earth's gravity field. For a successful mission, the reflectors must be kept as clean as possible for as long as possible. This imposes a stringent out-gassing requirement upon SURFSAT which must be taken into account when the team selects the materials and techniques to be used during the fabrication of the structure. Other restrictions that have to be met in order to allow the primary payload the highest possible chance of success include making sure the spacecraft is safe and inert during launch, and satellite mass and size limits are met.



KEY:

A: Existing Hardware Design
B: New Adapter (Height and Diameter to be announced)
C: SURFSAT (Exact position to be announced)
D: DELTA II Second Stage
E: Payload "X" (This can be another SURFSAT spacecraft.)
F: Modified Launch Adapter
G: LAGEOS III (Diameter = 2 ft.)
H: Payload Fairing (Diameter = 9.5 ft.)

Figure 5. Current predicted payload launch configuration. (i.e., without a spintable)

The current design meets these restrictions by fulfilling a combination of externally- and self-imposed requirements. It is roughly a 1-foot cube with a mass of 10 kilograms. Each corner provides mounting surfaces for an antenna or emitter with diametrically opposite corners occupied by emitters of the same frequency (see Figure 6). By using very-low-gain antennas in this arrangement, full isotropic coverage can be achieved regardless of the satellite's orientation in relation to the Earth. This arrangement is the result of an early decision to not use any form of attitude control once the spacecraft has been placed in orbit.

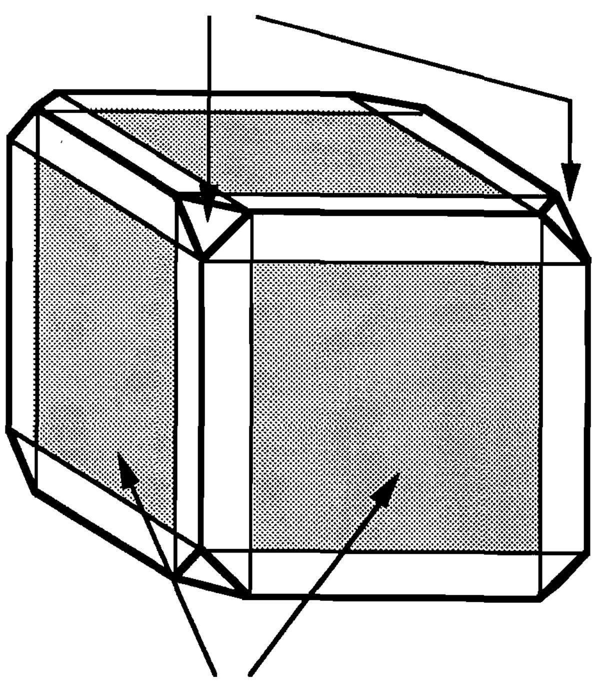


Figure 6. Proposed SURFSAT Design.

Attitude stabilization at a 6000-km. altitude invariably requires either complex mechanisms or potentially explosive propellants or both. In an effort to keep the satellite's design simple and avoid endangering either the launch vehicle or the primary payload, the spacecraft will be allowed to tumble through space. Tumbling the spacecraft has the additional important advantage of keeping it at a uniform thermal state. Thus the spacecraft does not have to resort to using dedicated thermal radiators, which use up precious volume and mass, in order to stay within a "comfortable" temperature range.

Electrical power will be solely generated by solar arrays mounted on each face of the cube. This will guarantee a continuous and adequate power supply for the spacecraft's operations regardless of its tumble orientation and spin rate, without having to resort to batteries, which pose a severe mass penalty. Furthermore, the presence of batteries onboard SURFSAT may endanger the primary payload or the launch vehicle during launch through outgassing.

A further restriction imposed on the satellite by LAGEOS III is the orbit. SURFSAT is constrained to operate at an orbit within 50 km of LAGEOS' orbit, which is currently baselined at 6000 km altitude and 70 degrees inclination. This has posed significant challenges to the project team because of the strong radiation environment found at that altitude. The most affected electrical component will be the solar arrays which, without adequate protection, will at least see a 60% degradation in their power-generating capacity over two years.

Shielding is also required for other electronic components. Unfortunately, the solutions that have been found to solve this problem eat into the mass budget and complicate the packaging problem, given the limited volume. LAGEOS III does not have problem with the radiation environment because it carries no electronics whatsoever. The orbit, however, does provide an adequate basis for the simulation of a deep space vehicle's motion and is high enough to allow a realistic approximation of its radio signals.

While these challenges are being overcome and a definitive design is in the process of being "frozen," the work has been moving at a less than desirable pace. The project has tended to move quickly during the summer but becomes near-dormant for the rest of the year. There also tends be a high turnover rate; most students tend to stay with the project for only a year before moving on, inducing a lack of continuity in the Project team's work. New students require a period of time with which to acquaint themselves with the Project and their respective summer tasks, causing some delays. This problem has been avoided to a certain degree by initiating Project orientation before the start of the summer.

Attempts to continue the Project's momentum during the academic year have involved the re-hiring of some of the students to continue work during the school year on an academic/part-time basis. This has proven to be a mixed success because of the heavy academic workload faced by the students.

Concluding Remarks and Future Plans

Much work still needs to be done: completing the development of various electronic components, the construction of each component and subsystem and full flight-qualification testing. Plans are being drawn up for the construction and testing phases. Despite certain drawbacks, the concept of using SURF students during the summer has proven to be successful in allowing highly able college students to gain hands-on experience in the planning and design of spacecraft. It has also served as an excellent college recruiting tool for JPL.

However, the project to build SURFSAT I and II will not end with their completion and launch. Work will continue as successive student teams operate the satellites. This phase of the project plans for students to participate in satellite tracking, data acquisition and data reduction to evaluate the performance of the SURFSAT K_a-band link and other experiments. The SURFSAT satellites will not be "one-of-a-kind" specials either. Instead, we hope that they will be the first examples of a whole line of student-built spacecraft capable of carrying progressively more complex experiments into space cheaply. These experiments will range from the testing of new telecommunications concepts and frequencies to the demonstration of new materials, components and equipment in the space environment.

Acknowledgement

The Project teams owe much of their progress to the outstanding aid provided by the members of the various groups at JPL connected to the design, construction and operation of spacecraft. In addition, the support provided by the Office of Telecommunications and Data Acquisition has also been superlative.

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References

1. Smith, J.G., "Ka-Band (32-GHz) Downlink Capability for Deep Space Communications," *TDA Progress Report 42-88*, Jet Propulsion Laboratory, Pasadena, California, October-December, 1985.

2. Dickinson, R.M., "Comparison of 8.415-, 32.0-, and 565646-GHz Deep Space Telemetry Links," *JPL Publication 85-71*, Jet Propulsion Laboratory, Pasadena, California, October 15, 1985.

3. Chow, J.K., and Ng, J.K., "Mission Specification (Preliminary), Microwave Microwatt Interferometry and Telemetry Experimental Satellite," *Summer Undergraduate Research Fellowship Paper*, California Institute of Technology, Pasadena, California, October 1990.

4. Borncamp, F., and Robbins, P., "SURFSAT I and II: Stage 2 Review." Jet Propulsion Laboratory, Pasadena, California, June 1991.