University of Arizona

STUDENT SATELLITE PROJECT

INITIAL DESIGN DOCUMENT

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1. SCIENCE

1.1 INTRODUCTION

STAR-FLASH is designed to perform two primary science missions: 1) lightning andsprite detection and 2) space-borne UBV photometry of standard stars. It is an f/7.0 Cassegrain telescope which will be launched from the Space Shuttle Orbiter using the Shuttle Small Payloads Project Hitchhiker Ejection System. A silicon photodiode will be used for sprite detection while lightning observations will be obtained with a 128x128 CCD. The photodiode will also be used in conjunction with a filter wheel to perform UBV photometry of the most commonly used Johnson UBVRI photometric standard stars.

The lightning detection experiment is intended to supplement the data collected by Marshall Space Flight Center's Lightning Imaging Sensor (LIS) which will fly in August of 1997 as part of the Tropical Rain Forest Measurement System. The basic design of the STAR-FLASH instrument was based on the LIS sensor with added enhancements to allow sprite detection and stellar photometry.

1.2 INSTRUMENT DESIGN

A schematic illustration of the STAR-FLASH instrument is shown in Figure 1.1. STAR-FLASH is an f/7.0 cassegrain telescope with a 15 cm primary mirror which incorporates external baffling 2 cm from the edge of the mirror to minimize stray light. A hyperbolic secondary mirror is mounted at the 1/3 point of the primary, supported by curved diagonal vanes which were chosen to minimize diffraction spikes. The 45 cm focal length primary is expected to provide a 50 by 50 degree field of view from the planned 250 km, 57 degree inclination orbit.

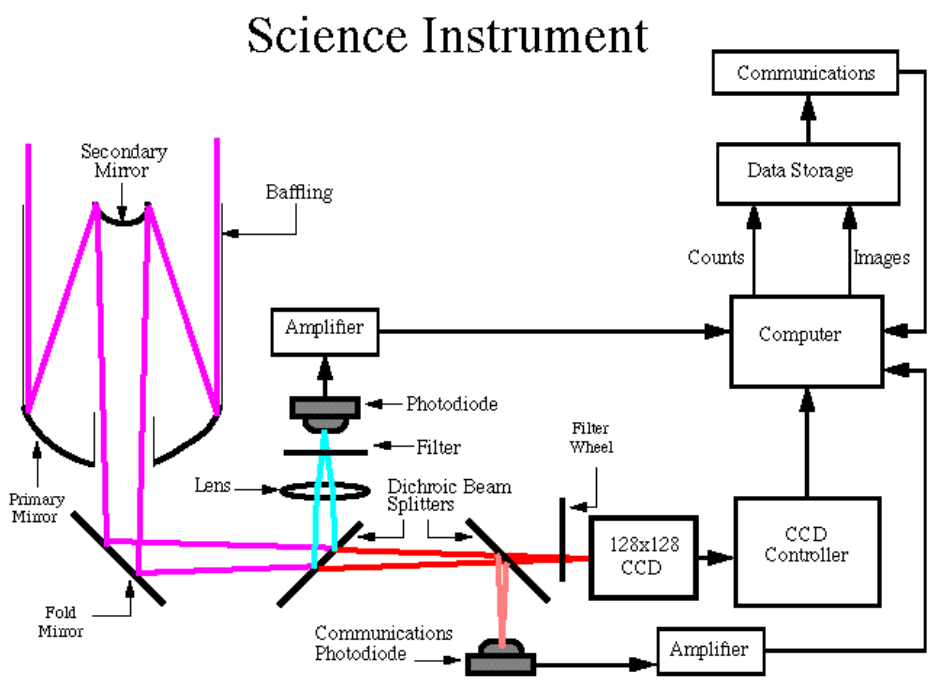


Figure 1.1 Science Instrument

A fold mirror behind the primary mirror reflects light from the secondary mirror to the first of two dichroic beam splitters. All light with a wavelength less than 700 nm will be diverted through a focal reducing lens and filter wheel, ultimately falling on a highly photometric and stable 0.1 mm silicon diode. This photodiode will be used for for both sprite detection and stellar photometry as described below.

The longer wavelength light will be passed on to the CCD for lightning detection and imaging, as described in section 1.3, below. A second dichroic beam splitter is incorporated upstream from the CCD for use in the laser communications experiment, described in the STI proposal.

Output signals from the photodiodes are amplified and sent on to the STAR-FLASH On-Board Computer (OBC), as are images from the CCD controller. The OBC processes the detector signals, and stores then for later downlink as described in the TTC proposal.

The Fold Mirror described above will be automatically adjusted to compensate for small dynamic pointing errors due to spacecraft nutation and guidance system perturbations. The necessary Fold Mirror adjustments will be accomplished by an electromechanical system which will employ feedback from both the STAR-FLASH CCD array and the satellite's Guidance Navigation and Control System.

1.3 LIGHTNING DETECTION AND IMAGING EXPERIMENT

The primary mission of STAR-FLASH is to count lightning flashes above the earth's surface. These simple observations will employ proven techniques to make a significant contribution to the database of lightning observations which will be produced by LIS, the Optical Transient Detector (OTD) and similar instruments.

Lightning observations are of considerable interest in a number of different areas. Lightning is an important indicator of global change. The prevailing theory of thunderstorm electrification postulates that lightning formation is driven by the collision of graupel and/or hail with ice crystals.Since graupel and hail can only form in deep convective systems where the updraft velocities are large, lightning can be used to locate regions of deep convection. With space-borne measurements it is possible to correlate intracloud as well as cloud-to-ground strikes with deep convection, whereas ground based sensors are limited to cloud-to-ground strikes.

Lightning is also a crucial element in the global "electric circuit". Thunderstorms facilitate the establishment of the Earth's "fair weather" electric field by transporting negative charge to the ground and positive charge upward from the cloud tops. Thunderstorms therefore act as "current generators", sustaining the potential difference between the Earth's surface and its ionosphere. Lightning discharges also generate a great deal of electromagnetic noise in the ionosphere (e.g. Schumann Resonances).

As indicated in Davis, et al. (1983) lightning may also substantially effect tropospheric chemistry, such as ozone formation and nitrogen fixation. (Sprites, described below, may also have a similar effect on stratospheric chemistry). The relationship between thunderstorm electrification and tornadogenesis may also be studied using a space-borne lightning detector and ancillary data.

As described in section 1.2, above, the STAR-FLASH instrument will incorporate a 128x128 CCD which will image lightening phenomena through a 777.4 nm filter. This wavelength was chosen for two reasons: 1) the relatively small intensity of solar radiation in this bandpass and 2) the presence of a very strong OI line in typical lightning spectra. When transients of sufficient magnitude are detected by the CCD, the corresponding image will be time-tagged and stored for later retrieval from the satellite.

1.4 SPRITE DETECTION EXPERIMENT

STAR-FLASH will also collect data on mesospheric phenomena known as sprites, which have generated considerable interest during the past few years. Sprites are large-scale (~1000 cubic kilometers), short duration (16 ms) optical transients which have been observed above regions of thunderstorm activity. Sprites typically extend from the cloud tops to as high as 100 km, and are most frequently centered at an altitude of about 66-74 km. These electrical discharges, which usually have a reddish color, are known to be prevalent above Mesoscale Convective Systems (MCS, which are on the order of 100 km on a side) as well as in regions where positive cloud-to-ground lightning discharges dominate (Sentman et al., 1995). Those authors detected an average of one sprite for every 200-300 cloud (lightning) flashes, during observations made over the central United States.

Although space-borne observations of sprite phenomena have been made during the Mesoscale Lightning Experiment, which used the payload bay camera on Space Shuttle Orbiter, many questions remain to be answered, including: a) can a land/ocean bias in sprite frequency be established? b) do correlations exist between the frequency of sprites (relative to cloud flashes) and such other factors as latitude, season or storm intensity? c) can sprites occur over single thunderstorm cells? d) what role do sprites play in the global electric circuit? e) does sprite frequency correlate to positive cloud-to-ground strikes? The continuous, long term sprite observing campaign which we propose can resolve many of these questions.

Although the STAR-FLASH instrument design is modeled after LIS, which is a nadir-pointing instrument, in order to detect sprites, our satellite will be required to point at the Earth's limb. This will allow our instrument to distinguish the faint sprite phenomena from the much brighter lightning flashes that occur beneath them. Our limb-looking optical train has the added advantage of enabling our instrument to view the same MCS over a longer period of time, thereby obtaining a larger statistical sample for each storm with a smaller field a view.

The spectral characteristics of sprites are similar to those of auroral electron precipitation for the first positive bands of molecular nitrogen (Hampton, et al., 1996). Sprite spectra therefore contain a broad peak from about 650 nm to 690 nm. Fortunately there is a large region of relatively low intensity emission in the near infrared lightning spectrum, from the 656.3 nm H alpha line to the 744.2 nm NI line. We intend to exploit these spectral characteristics to develop a sprite recognition algorithm, subtracting a 670 nm image from an image taken at 777.4 nm (where both sprites and lightning will be visible).

1.5 UBVRI STELLAR PHOTOMETRY EXPERIMENT

The STAR-FLASH orbiting telescope will also be uniquely positioned to perform measurements of the brightest Johnson UBVRI photometric standard stars with unprecedented accuracy.

Standard star measurements are used extensively to correct for air mass and atmospheric effects in many different astronomical applications. Ground-based measurements of standard stars are limited to a few hundredths of a magnitude RMS scatter for typical photometric measurements. Although ground-based RMS accuracies of a few thousandths can be obtained by co-adding 100 successive measurements, this method relies on the assumption that all deviations are completely random. This is clearly not an extremely reliable premise, since many systematic variables could affect such observations. Space-based measurements using the STAR-FLASH telescope would provide a much more accurate and reliable data set for these often-used standard stars.

As a minimum, we propose to observe the 20 or so brightest Johnson UBVRI photometric standard stars, though more than 100 stars brighter than magnitude 2.5 could be measured by this experiment, if the mission lifetime permits. In light of the ubiquitous use of the standard stars, this proposed science mission would provide an important contribution with far-reaching long-term benefits to the astronomical community.

STAR-FLASH will also provide an excellent platform to investigate stellar micro-magnitude variations, possibly verifying whether several recent detections of extra-solar planets are due to stellar oscillations or actual spectral Doppler shifts.

The figures in Table 1.1 and Table 1.2 verify the technical feasibility of the Stellar Photometry experiment. The expected photometric fluxes and signal-to-noise ratio (SNR) for the standard Johnson UBVRI filter set are shown in Table 1.1. Table 1.2 presents the expected SNR for the U and V passband for a typical silicon diode detector as a function of integration time.

Table 1.1 Expected Photometric Fluxes and SNR					
	U	B	V	R	I
Zero mag. absolute Flux Level (10^{-12} w/cm^2 μ)	4.35	7.20	3.92	1.76	0.83
λ_{eff} (μ)	0.36	0.44	0.55	0.70	0.90
Filter equiv. width (μ)	0.066	0.095	0.089	0.206	0.255
Flux in filter for one second integration, 5 cm diameter aperture, overall efficiency = 0.50					
0th mag. (10^{-12} joules)	2.82	6.72	3.43	3.56	1.83

Table 1.2 U and V passband expect SNR for typical Si diode detector NEP of 1x10^{-14} watts/sqrt(hz) and for integration times of 1, 10 and 100 seconds						
SNR		U		V		
	1s	10s	100s	1s	10s	100s
0th mag.	282	891	2820	342	1983	3420
1st mag.	112	355	1120	13.6	431	1362
2nd mag.	44.67	141	497	59.2	172	542

1.6 Schedule

Note: this schedule has been evolved to meet pre-defined Project Milestones and assumes that a) material and manpower requirements will be met by project management and b) scheduling of other team's activities are coordinated by project management. We believe that, in practice, the pre-defined Project Milestones may not be feasible.

Table 1.3 Science Instrument Schedule	
Preliminary Design & Prototype Fabrication	14 June 1997 - 3 Oct. 1997
Define Detailed Component Requirements	14 June 1997 - 30 July 1997
Complete Detailed Design Drawings	14 June 1997 - 30 July 1997
Obtain Materials for Prototype Model	14 June 1997 - 30 July 1997
Assemble Optical Train for Sprite Detection	30 July 1997 - 15 August 1997
Electronic Circuit Design	30 July 1997 - 15 August 1997
Build Filter Wheel System	15 August 1997 - 30 August 1997
Breadboard Electronic Components	15 August 1997 - 30 August 1997
Interface CCD/Controller/Computer	30 August 1997 - 15 Sept. 1997
Incorporate CCD in Optical Train	15 Sept. 1997 - 30 Sept. 1997
Incorporate Communications Photodiode	15 Sept. 1997 - 30 Sept. 1997
Build Telescope Prototype	15 Sept. 1997 - 30 Sept. 1997
Field Test Prototype	1-5 Oct. 1997
Preliminary Design Review	6-8 Oct. 1997

Detailed Design of Engineering Model	9 Oct. 1997 - 1 December 1997
Electronic Circuit Design	9 Oct. 1997 - 1 Nov. 1997
Design Fold Mirror Electro-mechanical System	9 Oct. 1997 - 1 Nov. 1997
Define Detailed Component Requirements	1 Nov. 1997 - 30 Nov. 1997
Complete Detailed Design Drawings	1 Nov. 1997 - 30 Nov. 1997
Obtain Materials for Engineering Model	1 Nov. 1997 - 30 Nov. 1997
Field Test Prototype Model Changes	1-7 December 1997
Critical Detailed Design Review	8-10 December 1997
Engineering Model Fabrication	15 Dec. 1997 - 15 Feb. 1998
Build Telescope	15 Dec. 1997 - 15 Jan. 1998
Build Fold Mirror Electro-mechanical System	15 Dec. 1997 - 15 Jan. 1998
Build Filter Wheel System	15 Dec. 1997 - 15 Jan. 1998
Assemble Optical Train for Sprite Detection	15 Jan. 1998 - 1 Feb. 1998
Build Electronic Components	15 Jan. 1998 - 1 Feb. 1998
Interface CCD/Controller/Computer	15 Jan. 1998 - 1 Feb. 1998
Incorporate CCD in Optical Train	15 Feb. 1998 - 30 Feb. 1998
Incorporate Communications Photodiode	15 Feb. 1998 - 30 Feb. 1998
Field Test Engineering Model	30 Feb. 1998 - 15 March 1998
Detailed Design of Flight Model	15 Feb. 1998 - 15 April 1998
Flight Model Fabrication	15 April 1998 - 28 August 1998
Lightning Field Test Engineering Model	1 July 1998 - 30 August 1998
Simulated Science Mission	15 September 1998
Instrument Testing calibration	18 May 1998 - 18 July 1998
Integration	31 August 1998 - 26 Feb. 1999
Final Testing and Calibration	29 Feb. 1999 - 26 May 1999
Simulated mission with complete satellite:	29 May 1999
Ready For Delivery:	5 June 1999
Ready For Launch:	TBD
Launch:	TBD

1.7 Division of labor

Estimates for manpower requirements and division of labor are presented in Table 1.4.

Table 1.4 Division of Labor		
Task	Discipline	Number of People

Library Research	Astronomy/Physics/AME	7
Mission Definition & Design	Astronomy/Physics	5
Instrument Design	Optical Engineering	2
Optical Design & Fabrication	Optical Engineering	10
Electric Circuit Design	Comp., Elec. Engr.	10
Electronic Circuit Fabrication	Comp., Elec. Engr.	5
Design Drawings	Drafting	5
Housing and Filter Wheel Fab.	Mech. Engr.	3
Fold Mirror Electro-Mechanical	Elec., Mech., Comp. Engr.	2
Field Testing	Astronomy/Physics	4
Administrative	Business	1
Data Processing & Analysis	Astronomy/Physics	5

1.8 Estimated budget

Table 1.5 Estimated Science Instrument Budget		
15 cm Parabolic Primary Mirror and Matched Secondary	$9000	15 hours labor
2 Johnson UBV filter sets	$500	
2 Polarization filter sets	$600	
2 Filter Wheels	$550	40 hours labor
2 Filter Wheel Driver Motors	$100	10 hours labor
Fold Mirror	$250	
Fold Mirror Mounting Hardware	$200	
Fold Mirror Electromechanical System	$2500	60 hours labor
2 Dichroic Beam Splitters	$10000	20 hours labor
Lens	$1500	
Highly photoelectric and stable Silicon Photodiodes	$1000	30 hours labor
Silicon Photodiode Amplifier & associated Electronics	$1500	60 hours labor
128x128 CCD array	$1000	20 hours labor
CCD Controller	$1500	80 hours labor
Control Computer & Peripherals	$1900	50 hours labor
Housing	$650	30 hours labor
Travel	$1500	
Misc. Fabrication	$500	60 hours labor
Test and Integration	$500	90 hours labor

access to mentorship in the field of electronic digital design
access to machine shop training and facilities to manufacture filter wheels

1.9 Available and Missing Tools, Components and Facilities

1.9.1 Tools Needed

- Laser
- Optical Test & Alignment Instruments
- Voltmeter
- Amp Meter
- Oscilloscope
- Basic Hand Tools

1.9.2 Tools Available

Optical Bench

1.9.3 Components Needed

1.9.3.1 Prototype Hardware:

- 15 cm Parabolic Primary Mirror
- Secondary Mirror
- 2 Johnson UBV filter sets
- 2 Polarization filter sets
- 2 Filter Wheels
- 2 Filter Wheel Driver Motors
- Fold Mirror
- Fold Mirror Mounting Hardware
- Fold Mirror Electromechanical System
- 2 Dichroic Beam Splitters
- Lens
- Highly photoelectric and stable Silicon Photodiodes
- Silicon Photodiode Amplifier & associated Electronics
- 128x128 CCD array
- CCD Controller
- Control Computer & Peripherals
- Housing

1.9.3.2 Engineering Model Hardware:

- 15 cm Parabolic Primary Mirror
- Secondary Mirror
- 2 Johnson UBV filter sets
- 2 Polarization filter sets
- 2 Filter Wheels
- 2 Filter Wheel Driver Motors

- Fold Mirror
- Fold Mirror Mounting Hardware
- Fold Mirror Electromechanical System
- 2 Dichroic Beam Splitters
- Lens
- Highly photoelectric and stable Silicon Photodiodes
- Silicon Photodiode Amplifier & associated Electronics
- 128x128 CCD array
- CCD Controller
- Control Computer & Peripherals
- Housing

1.9.3.3 Flight Model Hardware:

- Primary Mirror
- Secondary Mirror
- 2 Johnson UBV filter sets
- 2 Polarization filter sets
- 2 Filter Wheels
- 2 Filter Wheel Driver Motors
- Fold Mirror
- Fold Mirror Mounting Hardware
- Fold Mirror Electromechanical System
- 2 Dichroic Beam Splitters
- Lens
- Highly photoelectric and stable Silicon Photodiodes
- Silicon Photodiode Amplifier & associated Electronics
- 128x128 CCD array
- CCD Controller
- Control Computer & Peripherals
- Housing

1.9.4 Components Available

None

1.9.5 Facilities Needed

- Vacuum Chamber
- Machine Shop Training and Facilities
- Thermal & Vibration Test Chamber

1.9.6 Facilities Available

Clean Room for Final Assembly

1.10 REFERENCES

1. Boeck, William L., Otha H. Vaughan Jr., Richard J. Blakeslee, Bernard Vonnegut, Marx Brook and John McKune, Observations of lightning in the stratosphere, Journal of Geophysical Research, 100 1465-1475, 1995.

2. Davis, M.H., Marx Brook, Hugh Christian, Brian G. Heikes, Richard Orville, Chung G. Park, Raymond G. Roble and Bernard Vonnegut, Some Scientific Objectives of a Satellite-Borne Lightning Mapper, Bulletin of the American Meteorological Society, 64, 114-119, 1983.

3. Hampton, D.L., M.J. Heavner, E.M. Wescott and D.D. Sentman, Optical spectral characteristics of sprites, Geophysical Research Letters, 23, 89-92, 1996.

4. Sentman, D.D., E.M. Wescott, D.L. Osborne, D.L. Hampton and M.J. Heavner, Preliminary results from the Sprites94 aircraft campaign: 1. Red sprites, Geophysical Research Letters, 22, 1205-1208 1995.

2. Mechanical Structure and Stress Analysis

2.1 Abstract

The mechanical structure of a satellite is the platform upon which the scientific and operational instruments are placed. This structure must be lightweight, and resistant to thermal fluctuations, fatigue, fracture, and corrosion. Furthermore, it must provide stability to the instruments against undesirable vibrations and shocks during launch and transportation, and dissipate heat from the internal components.

We will design a hull and framework around the various internal components of the satellite, whose specifications will comply with the requirements listed for the Hitchhiker Ejection System (HES). A cylindrical design will be used to maximize internal volume and minimize the number of joints. Materials being considered include Graphite/Epoxy and Aluminum alloys. Coatings may be used to assist in strengthening the hull and reflecting electromagnetic radiation. Many of the necessary tools and facilities needed for fabrication and assembly of structural components are on-site at the University of Arizona through the Aerospace & Mechanical Engineering (AME) and Physics & Atmospheric Science (PAS) departments.

2.2 Goals and Specifications

We will design a hull and framework around the various internal components of the satellite. The internal structure will give support to the components during assembly, launch, and ejection until the only forces are caused by thermal expansion or gradients, torque from attitude control, or microgravatation. The hull and inner casings will protect the components from the environment at our orbital altitude. The maximum dimensions for the satellite are established by the requirements of the Hitchhiker Ejection Table 2.1).[1] Other detail specifications will be dependent on the needs of the scientific experiments as well as the internal components.

2.3 Design Approach

The design approach used by the mechanical team consists of the following steps:

1. <u>Initial Criteria for the Satellite</u>- This was determined by the specifications of the HES (Table 2.1) and requirements imposed by other teams.

2. <u>Preliminary Design</u>- A cylindrical design was selected to use all the available volume for the scientific experiments and equipment. Volume is limited by the HES, the maximum possible satellite volume is ~0.094 cubic meters (94,000 cubic centimeters).

3. <u>Material Selection</u>- The important characteristics that are demanded are strength, stiffness, low density, uniform coefficient of thermal expansion between the hull and frame, low specific heat, low cost, and machineability of the material.

4. <u>Modeling</u>- Computer modeling will determine the structural integrity of the preliminary design. Finite element analysis programs such as ANSYS, will be used to check stresses and thermal expansion and contraction over many cycles. Pro-Engineer will be used to do the geometrical modeling.

5. Final Design- With size and mass specifications for all components known final modeling can be performed, and a final design can be selected.

6. Fabrication- For the most part we will use the tools and facilities of the AME and Physics departments to fabricate the hull and structure. However due to NASA policy and/or limitations on our facility's capabilities, it may be required to have some parts fabricated for us.

7. Assembly- Integrating components together will be done during the assembly process. All electrical wiring will be protected with braided Teflon shielding, and "staked" to the structure with epoxy, Teflon zip-ties, and/or unwaxed lacing cord.

Testing- The satellite will undergo vibrational, space-environmental and thermal tests within the AME department and/or at outside facilities (Hughes, JPL, and perhaps others).

Table 2.1 Hitchhiker Ejection System Parameters	
Maximum spacecraft weight	68 kg (150 lb)
Maximum spacecraft height re separation plane	52 cm (20.5 in)
Maximum spacecraft diameter	48 cm (19 in)
Canister inside diameter	50 cm (20 in)
Maximum CG location re canister centerline	1.27 cm (0.5 in)
Maximum CG location re separation plane	26 cm (10.25 in)
Ejection Velocity (at 68 kg)	0.6 - 1.2 mps (2 - 4 fps)
Maximum rotational impulse at ejection	To Be Determined
Minimum payload resonant frequency	To Be Determined (Hz)

2.4 Fabrication Approach

The selection of materials is somewhat dependent on the requirements of the other teams. Important characteristics are the comparative specific strengths and stiffness (Illustrations 1 and 2), and thermal properties. The available materials that best meet these requirements are:

- Carbon/Epoxy - Low coefficient of thermal expansion. Higher strength and lower cost than Graphite/Epoxy.
- Graphite/Epoxy - Low coefficient of thermal expansion. Stiffer, therefore less deflection of the structure than Carbon/Epoxy. Low density.
- Aluminum - Cheap, easy to work with. Higher coefficient of thermal expansion than Carbon composites.
- Aramid - a type of Kevlar (Dupont B84), very strong.
- Boron/Epoxy - extraordinarily hard (comparable to a diamond), difficult to machine.
- Carbon/Carbon - extraordinarily strong, highly resistive to corrosion, difficult to acquire, very expensive.

Histograms of material specific strengths and specific stiffness taken from *Composite Materials for Aircraft Structures* (Hoskin, B.C. and Baker, A.A., AIAA, New

York (1986), p. 40) are presented below in Figure 2.1 and Figure 2.2 respectively. Comparative properties of composites are shown in (Hoskin and Baker, p. 62)

Figure 2.1 Comparison of Composites and Metals by Specific Strength

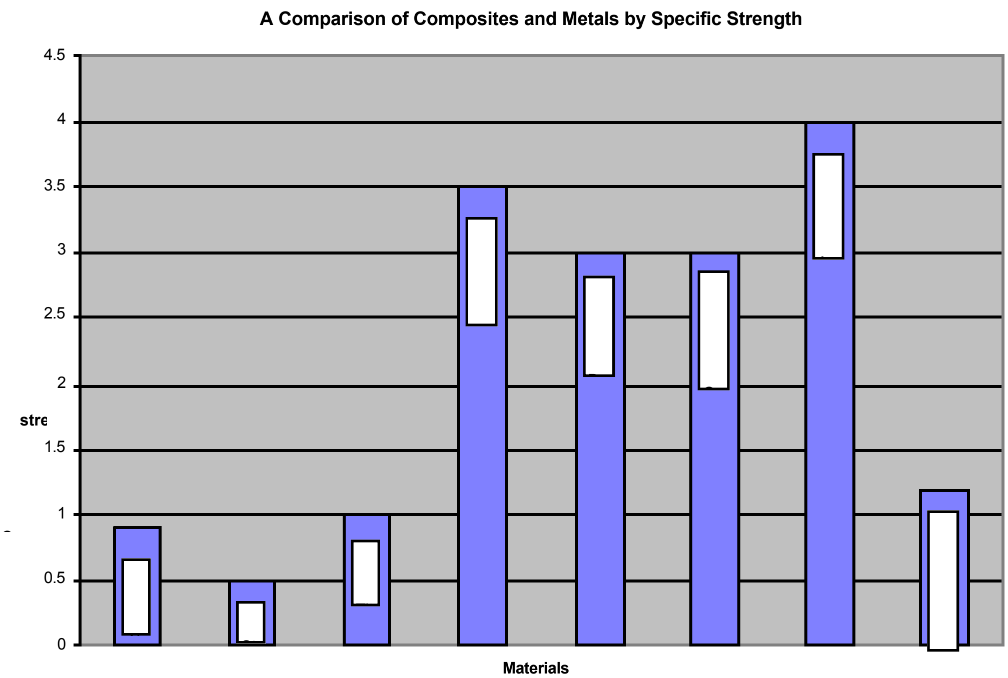


Figure 2.2 Comparison of Composites and Metals by Specific Stiffness

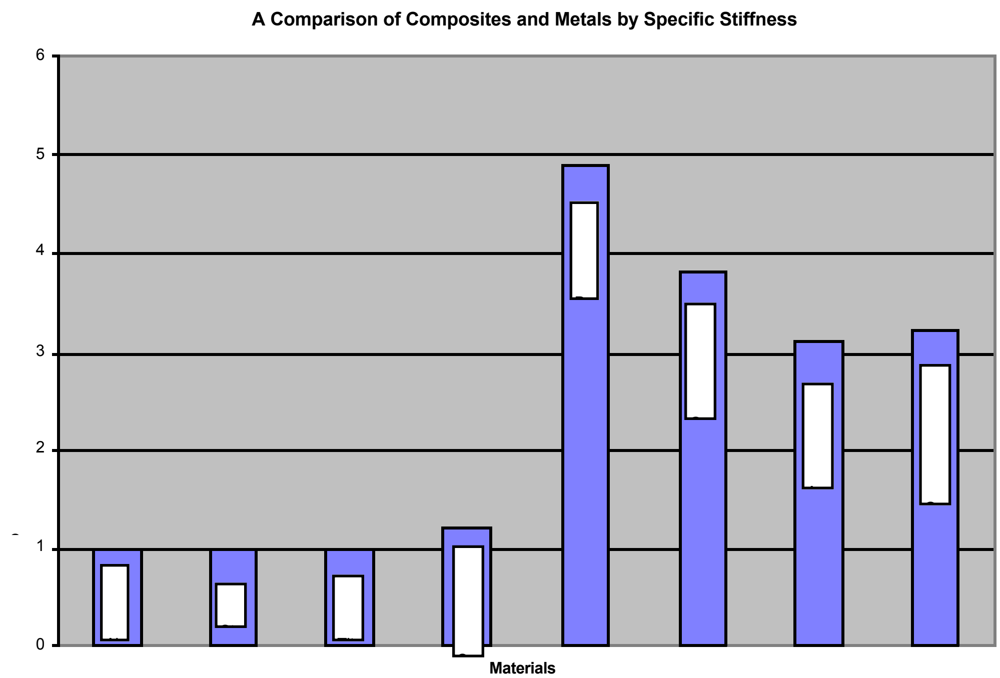


Table 2.2 Comparative Properties of Composites and Metallic Aircraft Materials					
Material	Specific Gravity	Tensile Strength (Gpa)	Tensile Modulus (Gpa)	Specific Tensile Strength (Gpa)	Specific Tensile Modulus (GPa)
Boron/Epoxy	2.0	1.49	224	0.73	110
Graphite/Epoxy, type I	1.6	0.93	213	0.58	133
Graphite/Epoxy, type II	1.5	1.62	148	1.01	92
Aramid/Epoxy	1.45	1.38	58	0.95	40
Glass/Epoxy	1.9	1.31	41	0.69	22
Steel	7.8	0.99	207	0.13	27
Aluminum alloy	2.8	0.46	72	0.17	26
Titanium	4.5	0.93	110	0.21	24

The material that best meets demands is Graphite/Epoxy due to stiffness requirements. Ideally we would like to use the same material (Graphite/Epoxy) for both the interior frame and the hull in order to minimize the effects of thermal expansion. However, we anticipate that one or more constraints (e.g. cost, stiffness, etc.) will force us to use of a combination of materials. Stress analysis programs (e.g. ANSYS) will calculate the points of high stresses within the structure while taking into consideration the differences of thermal expansion in different materials, linear acceleration, structurally transmitted vibration, shock, acoustic loads, and internal pressure. These programs will also assist us in determining where additional support is needed. An area of great concern is the distribution of thermal energy over the hull's surface as it is subjected to orbital thermal cycles.

We intend to mold the Graphite/Epoxy hull in a cylindrical shape, with two circular pieces making up the top and bottom of the hull of the craft which can be adhesively bonded to upper and lower reinforcing rings. The interior structure will consist of thin strips of material (Graphite/Epoxy, Aluminum, etc.), bonded to cylinder walls and/or reinforcing rings and spanning across the cylinder in "key" positions. "Key" positions will be determined by stress analysis after internal loads have been specified.

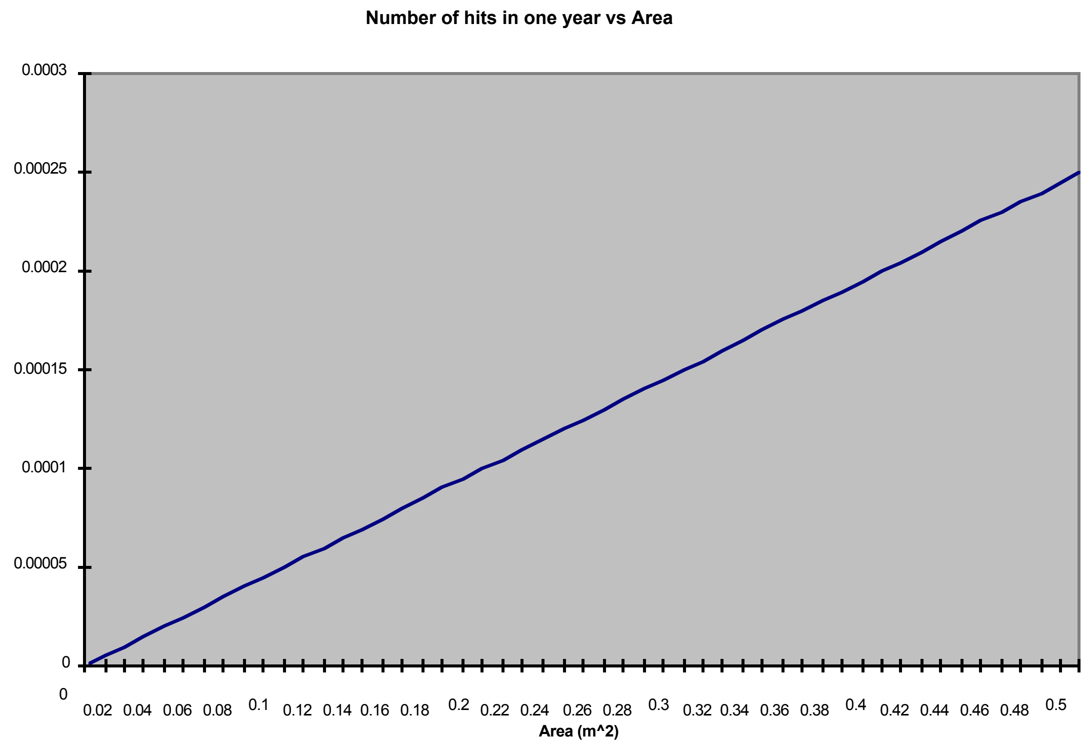
The amount of interior space allocated to each team will be determined by compromise between what is wanted and what is necessary to best meet the objectives of the project. Each team's components will be arranged such that the mass is distributed throughout the craft in such a way as to reduce the stresses at the mounting interface during launch, and (if needed) provide a stable axis of satellite rotation. A 9.375 inch in diameter plate will be affixed to the "bottom" of the craft to connect it to the Space Shuttle's HES canister with a Marmon Clamp mechanism.[1]

For additional strengthening of outer hull or casings of components it is common to use coatings. Coatings can be sprayed onto the surface of the desired material, and also provide protection against radiation and corrosion. Reflective coatings are beneficial for low heat absorption and high emitance. The Optical Sciences department produces an excellent reflective coating; it is a silver layer coated with silicon oxide to prevent the silver from eroding. However if this method is too costly, then we can use a traditional white paint (S13GLO is generally considered the best white paint available for spacecraft).

In the case of joining Graphite/Epoxy with an electrically conductive metal (e.g. Aluminum), the surfaces must be insulated from each other due to the electrically conductive properties of Graphite/Epoxy. This avoids the danger of galvanic corrosion on the metal side of the joint. Furthermore, several electrical components will be in operation (e.g. lightning detector, CCD Camera, communications system, etc.) that may produce a significant static electrical charge, requiring discharge.

For long-term operation erosion from atomic oxygen and other particles must be considered, Beta-cloth (a Teflon impregnated porous fiberglass) may be used to reinforce the hull. Even though the hull will be very strong, once in a great while (one chance in eight thousand that a collision will happen in a year for a satellite our size: Figure 2.3)[2] a particle will "blast" through the thin hull. If it is deemed necessary, we can use a Warm Electronic Box (WEB, a shell of Aramid) to encase the vital component(s).

Figure 2.3 Number of hits in one year vs. area



2.5 Schedule

1997

June- Attain machine-shop certification from AME, set-up Pro-Engineer training with Hughes. Continue research of materials, software, available facilities and equipment.

July- Clean out and set up room (AME N417B) to use as project workspace. Integrate with other components to form a computer aided preliminary design for mock-up. Arrange AME and Physics department financing of mock-up materials. Order mock-up materials (probably fiberglass since it has a very similar fabrication process to Graphite/Epoxy)

August- Composite materials training in the Composite Lab (AME N441) Building of mock-up. Pro-Engineer training.

September- Integrate in new Fall Semester team members, preparation for preliminary design review.

October- Preliminary design review (Oct. 6-8), detailed design.

November- Detailed design, preparation for critical design review

December- Critical design review (Dec. 8-10), vacation.

1998

January- Integrate new Spring Semester team members

February & March- Computational modeling, prepare for fabrication.

April & May- Fabrication and Machining.

June & July- Preliminary physical testing.

August through December- Component integration.

1999

January & February- Final integration and assembly.

March through May- Final testing.

June- Satellite ready for delivery.

2.6 Division of Labor

We are anticipating approximately twenty students for our team with help from four professors to act as mentors in their areas of expertise. A generalized division of labor will allow students to pursue their particular interests while encouraging their general interest in the following duties:

- Machinists - four AME machine-certified students with one mentor.
- Composite Fabricators - four students with one mentor.
- Computer Drafting and Analysis Operators - four trained students with two mentors.
- General Technical Support - eight (or remaining) students.

2.7 Available Facilities and Equipment

Manufacturing of most of the composites listed can be fabricated and machined on campus through University facilities (composite lab, machine shop, etc.), outside facilities may be needed for physical testing. With the exception of Aramid (a "huge" roll is available in the AME building), we still need to obtain all materials for the structure. We will have computer labs with programs such as ANSYS, ABAQUS, Pro-Engineer, and AutoCAD available for our use.

2.8 Estimated Budget

Cost of Materials and Supplies- The Graphite/Epoxy hull may have to be purchased if our facilities are inadequate at a (currently) unknown price. Current prices of some raw materials are approximately $8 per pound for graphite and approximately $2 per pound for aluminum. We will also need tools (drill bits, hand tools, etc.), safety equipment (safety glasses, gloves, etc.), general supplies (nuts and bolts, epoxy, etc.), and petty cash for miscellaneous expenditures.

Rent-

Outside testing facilities may need to be rented.

Labor Hours-

Fall & Spring Semesters: Twenty students working an average of three hours a week for 32 weeks gives a total of 1920 student hours. Four mentors donating a combined total of five hours per week gives a total of 160 mentor hours during the fall and spring semesters.

Summer Sessions: Ten students working an average of three hours a week for 10 weeks gives a total of 300 student hours. Two mentors donating a combined total of two hours a week for the ten weeks gives 20 mentor hours for the summer.

Total:
2220 Student Hours per Year
180 Mentor Hours per Year
2400 Hours per Year

2.9 References

1 *Hitchhiker customer Accommodations and Requirements Specifications*, HHG-730-1503-07, pages 2-144 and 2-145

2 Plot made from data in *The Space Environment*, AME 424/524 Fall 1993 Handout #2, compiled by Dr. Ramohalli (AME Dept., Univ. of Arizona)

3. Guidance, Navigation and Control

3.1 Goals & Specifications

The purpose of the guidance, navigation and control subsystem is to provide the satellite with the proper orientation and stability to point its instruments in the correct direction. The science mission involves both earth observation for the lightning and laser communication system and inertial pointing for the photometry experiment. The only feasible control schemes which allow earth pointing are the gravity gradient method and three axis stabilization (although rotation about the pointing axis can be permitted). Gravity gradient control only allows pointing accuracy of ~5°, and requires the structure of the satellite to be designed in such a way that the gravity gradient torque is the largest environmental torque on the system, which is usually implemented in the form of a long boom. The satellite will be traveling in a Low Earth Orbit (LEO) (altitude 185-400km, inclination 51°). For these orbits the aerodynamic drag is the dominant disturbance (see Table 3.1 for an estimate of the disturbance torques) and an order of 10^5 larger than the gravity gradient. Therefore, we propose to use 3-axis stabilization which also allows inertial pointing for the photometry experiment.

Table 3.1 Estimate of disturbance torques for LEO (attitude: 185-400km, inclination: 51)

Disturbance Source	Estimated Torque (Nm)
Gravity Gradient	6.43E-7
Solar Pressure	1.85E-7
Magnetic Field	2.69E-5
Aerodynamic Drag	.04

After the control scheme has been decided, the next step is to determine the performance criteria the control must deliver. The first criteria is that the control system must be able to stabilize the satellite; otherwise, it will be uncontrollable. The actuators must be able to at least counteract the disturbance torques - from Table 3.1, actuators capable of applying torques on the order of .4 Nm will probably work, although actual simulations must be done to determine the exact numbers. The next criteria is to point the satellite at the earth; this requires constantly changing the satellites orientation, 360° every orbital period. For a typical LEO, this amounts to around .3°/sec (again, the actual amount must be determined from simulations). The last criterion is the pointing accuracy to be maintained by the system. This is largely set by the requirements of the science mission. As presently understood, the lightning and laser communication experiment require only an accuracy of 1-5° around each axis. The photometry experiment will require an accuracy of 0.1° which probably will necessitate going from team-built sensors to commercial ones and a correspond 10-1000 fold increase in price (some of the commercial sensors are upwards of $850k). The telemetry team does not require any pointing for their antennas.

Goal	Description
Type of control	• three axis inertial and earth pointing • Zero momentum based control

Slew rates	~.5° /second
Pointing accuracy	.1-0.5° in pitch, roll and yaw directions
Others	• The satellite will be traveling in LEO with an attitude of 185-400km and an inclination of 51° • The satellite will not be able to make changes in orbital parameters • Slewing maneuvers are necessary for: a) pointing the payload science instrument, b)maneuvering the GNC subsystem's sensors to celestial targets for attitude determination, c) acquiring the satellite after ejection from the Orbiter, d) re-acquiring the satellite after any potential subsystem failures or disturbances and e) "safe mode" stable position if the computer resets.

Table 3.2 Navigation, Guidance and Control specification

3.2 Design approach

First a brief overview of the approach will be given. A more detailed description of each module will be given in the next subsections.

A number of independent sensors will be used to provide redundant and self-verifying attitude determination. Course-scale sensors (order 1°)will include mapping the output of the solar power cells (or special solar cells) to determine the sun's location, a magnetometer to sense the earth's magnetic field vector, and a polarized data link with the ground station. Fine-scale sensors (order .1°) will be an optical sun sensor (or horizon sensor) and possibly using the science payload as an additional sensor.

Passive viscous dampers will be employed to ensure stability in the event of system failure. Two reaction wheels, one with the earth-pointing axis and one perpendicular to it, will be employed for primary attitude control, backed up by 3 magnetic torquers to provide momentum dumping and extra stability. Depending on the reaction wheels used, it might be possible to recapture the rotational energy.

A schematic drawing of the proposed GNC subsystem is provided in Figure 3.2, while a block diagram is shown in Figure 3.1. Table 3.3 summarizes the design approach. After this brief introduction the different modules will be described in more detail.

System	Components
Satellite	• Altitude 185-400km • inclination 51° • Duration < 1 year • max diameter 48 cm • max height 52 cm • max mass 68 kg
Actuators	• two reaction wheels • magnetic torquers • viscous dampers
Sensors	• sun sensor / horizon sensor

	• array of 6 small solar cells or use of solar power cells as coarse sun sensor • magnetometer • star tracker (using science instrument) • polarized radio transmission • Satellite's orbital state will be determined from a ground station tracking data uplink
Mounting sun sensor	Sun sensor should be mounted on one end of satellite for unobstructed view. Structural bending should be limited to assure pointing accuracy
Using solar power cells as coarse sun sensor	Work with PGD team
Star tracker	Using the science instrument as a star tracker. Use of beam splitter to divert portion of target's light onto CCD array
Polarized radio transmission	By polarizing the satellite's radio transmissions with respect to one of the satellite's principal axes will allow the ground tracking station to estimate the attitude and angular velocity of the satellite. Work with TTC team
Reaction wheels energy storage	Electrical energy will be recaptured when reaction wheels are slowed down

Table 3.3 Design approach guidance, navigation and control subsystem

3.2.1 Actuators

I. Reaction Wheels

In essence, a reaction wheel is an electric motor with a heavy disk attached to its axis. By applying a current to the motor, a torque can be generated by changing the angular velocity of the disk. According to Newton's third law, a reaction torque with the same magnitude and opposite sign will then act on the satellite. The control system uses this torque to reorient the spacecraft when a vehicle pointing error (deviation from the desired attitude) is detected by the GNC sensors.

When the cumulative value of the applied torques is much greater than zero, the reaction wheel will eventually reach its maximum rotational velocity (a condition referred to as saturation), preventing the application of any further torques. Saturation of a reaction wheel typical occurs when more torque is consistently applied in one direction than another, over a long period of time. Other actuators (see below) are needed to slow down the reaction wheel by applying an external torque. This process is called de-saturation, momentum unloading or momentum dumping.

While most reaction wheel systems employ three wheels, one along each axis, we propose to accomplish the same task using only two well placed, reaction wheels. This approach is possible because any arbitrary change in attitude can be represented by three consecutive rotations about two body-fixed axes, a fact which is well known to anyone who is familiar with Eulerian angles. A formal proof of the feasibility of this method is given by Walsh et al (1993) which includes the actual steering algorithms.
[G. Walsh, A. Sarti, S.S. Sastry, "Algorithms for steering on the group of rotations" in Proceedings of the American Control Conference, p1312-1316,1993]

Most of the mass of our proposed GNC subsystem resides in the relatively heavy reaction wheels. Using two wheels instead of three is very advantageous, as it will decrease the weight of the control system by approximately 25%. Although this method significantly increases the computational requirements of the control algorithms, we believe that the benefits of reduced cost and lower mass outweigh this disadvantage.

Although we do not know if it is a standard feature, we would also like to note that it is possible to recapture electric energy that is used to accelerate the reaction wheels. Electric energy is converted to kinetic energy when a torque is applied to increase the speed of a reaction wheel. One method of decreasing the wheel's speed is to use the motor as an electric generator, converting rotational kinetic energy back into electric energy. Although this approach requires special steering amplifiers which are able to supply energy back to the power supply, the result is a very energy-efficient actuation system; only energy that is needed to overcome external disturbances and internal friction is lost.

II. Magnetic Torquers

A magnetic torquer uses a magnetic coil or electromagnet to generate a magnetic dipole moment which interacts with the Earth's magnetic field to produce a torque on the spacecraft. This type of actuator produces a torque that is proportional to the varying intensity of the Earth's magnetic field, and so is more effective at lower altitudes. Magnetic torquers have no moving parts, requiring only a magnetometer for field sensing and a wire-wound electromagnetic rod along each axis. The resulting torques are rather small, and several orbits may be necessary to achieve complete momentum de-saturation of the reaction wheels. For more rapid momentum unloading and to provide rapid nutation dampening, our proposed GNC subsystem will also employ viscous dampers, as described in the next subsection.

III. Viscous Dampers

A viscous damper is a passive device which is used to remove angular momentum from the satellite. A viscous damper typically consists of a toroidal tube partly filled with a highly viscous liquid (mercury is commonly used). As the satellite rotates, the liquid forms into a plug as "centrifugal force" moves it to the point farthest away from the axis of rotation. As the satellite spins, this fluid plug remains relatively stationary, generating viscous drag against the tube walls, thereby converting rotational energy into heat. Sometimes a tube completely filled with a liquid and containing a solid ball is used instead. Viscous dampers represent a very mature and simple technology, which has already been used on a large number of satellites.

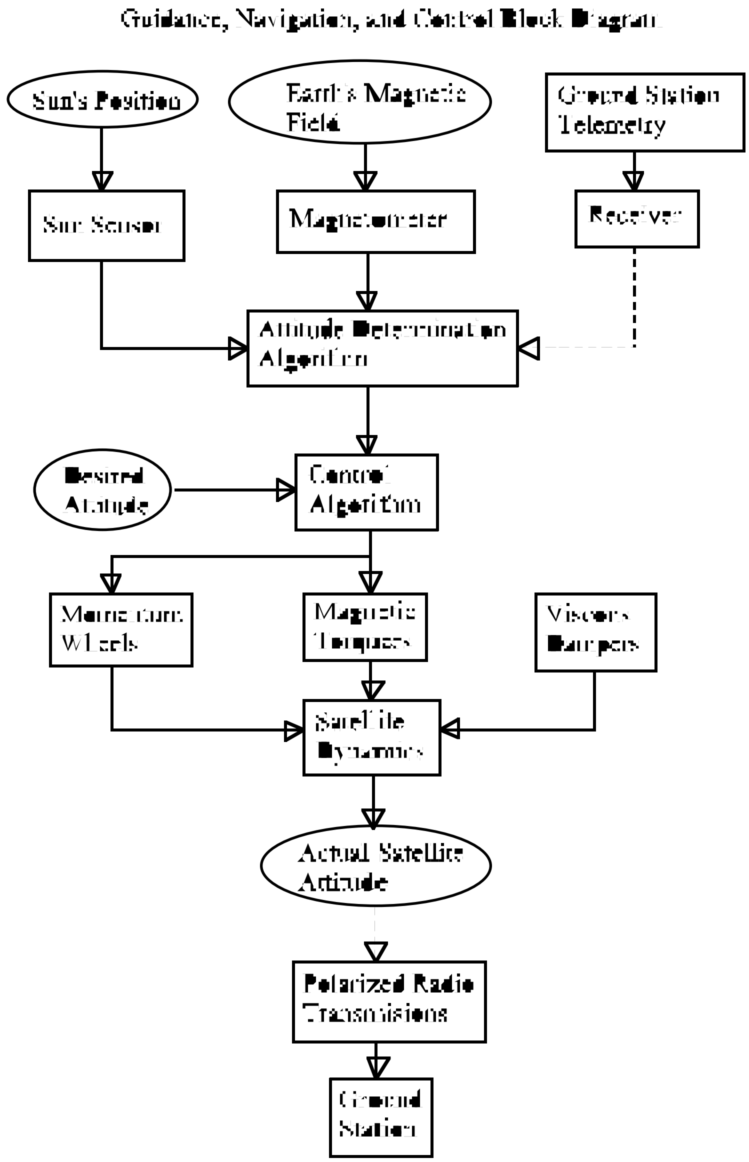


Figure 1

Figure 3.1 Guidance, Navigation and Control Block Diagram

3.2.2 Sensors

In order to obtain control information to drive the actuators described in the previous section, at least two sensors are needed to determine the attitude of the spacecraft. We will employ three primary sensors and two secondary sensors in our proposed GNC subsystem, as described in the following subsections.

3.2.2.1 Primary Sun Sensor and "Sun Sensor Array" (for coarse pointing)

We will employ a Sun sensor with an accuracy of 0.01 to 0.05 degrees to detect pointing errors along two axes of the spacecraft. The sun sensor will also be used to acquire or reorient the vehicle to an inertially referenced known attitude from an unknown or arbitrary attitude. The sun sensor should be mounted on one end of the satellite to provide an unobstructed field of view, typically the end opposite the science payload aperture. Our studies indicate that structural bending on the sun sensor mounting is the greatest limit on pointing accuracy; care should thus be taken to work closely with the structural engineering group to develop the most stable mounting surface for the sun sensor.

As an optional and redundant auxiliary sun sensor (with an accuracy of 1-5 degrees) we propose affixing 6 small solar cells to the spacecraft exterior housing as indicated in Figure 3.2. This "sun sensor array" will be used during normal maneuvers as a backup for the main sun sensor and to provide and additional attitude reference to re-acquire the satellite, should it become "lost" after any potential subsystem failures. As an interesting alternative, it may be possible to monitor the output from the main solar power cells to achieve this same end.

3.2.2.2 Magnetometer (for coarse pointing)

Since the magnetic torquer actuating system described above incorporates a magnetometer, we propose using that device as our second sensor. The magnetometer, which is simple and light-weight, will measure both the direction and size of the Earth's magnetic field. When compared with the Earth's known magnetic field, and the sun sensor's data, this output will establish the spacecraft's attitude to within 0.5 to 1.0 degree.

3.2.2.3 Star Tracker (for fine pointing)

To establish more accurate pointing than can be provided by the sun sensor and magnetometer system described above, we will utilize data from our assumed astronomical science payload. For the sake of discussion we will assume that the payload instrument is observing a star, or that at least one star will be present in the instrument's field of view. We will further assume that the science instrument will use a simple flip down mirror (or better yet, a beam splitter, with no moving parts) to divert a portion of their target's light onto a CCD array, silicon diode, or similar detector. Any vehicle motion will be manifested as motion of the target star's image, which can then be corrected using the reaction wheels described above.

3.2.2.4 Polarized Radio Transmission (for coarse pointing)

It is also possible to provide a simple auxiliary system to sever as a backup for the sensors described above, by polarizing the satellite's radio transmissions with respect to one of the satellite's principal axes. This will allow the ground tracking station to estimate of the attitude and angular velocity of the satellite, with little extra cost or added complexity.

3.2.3 Spacecraft Control

Computer hardware and software on board the satellite will decode the input signals from the sensors described above to determine the attitude of the satellite. A particular type of computer algorithm, known as an "observer" can be used to estimate the angular velocity of the satellite. An algorithm of this type uses a model of the satellite and a time history of the attitude information to generate an estimate of the spacecraft’s angular velocity. The control algorithm then uses this estimated angular velocity, along with the current and desired satellite attitude to compute appropriate actuator torques.

Selection of an optimal control algorithm is strongly dependent on the actual satellite systems and properties. As most of the spacecraft features are undefined at the present time, we shall specify the design criteria for the algorithm rather then deriving an explicit control law. The following requirements drive the selection of the control law: (1) accuracy, (2) robustness, (3) energy efficiency and (4) computational simplicity.

3.3 Fabrication approach

This will depend a great deal on whether sensors and actuators are purchased or built. If they are purchased, not much is needed. If built, the following will apply:

Magnetic Torquers: Special wire-winding skills/equipment will be needed (perhaps we can use equipment for rebuilding motors).

Sun/Horizon Sensor: Expertise in Optics/optical electronics needed. Probably special lens handling/assembly equipment will be needed (cleanroom?)

Electronics: It is very likely that will be building specialized circuits / electronics- will need PCB manufacturing.

3.4 Division of labor

Skill	Available?
2 Controls mentors	available
1 Space environmental mentor	need
1 Electronics mentor	need
4 Mechanical Engineering Students	available
2 Electrical Engineering Students	need 2
1 Physics/Astronomy Student	need

Table 3.4 GNC Division of Labor

3.5 Available and missing tools, components and facilities

Item	Availability
Assembly / testing space	Needed
Machine Shop	AME shop
Electronics Shop	Needed
Computers	2 personal PC's along with campus network available
-MATLAB - simulations	Have
-CAD package	-part time access to AutoCAD & PRO/E on 1 machine, more needed
-PCB layout/Circuit diagram/Simulation	Needed
Physical simulator	Must be built/fabricated or found

Table 3.5 GNC Available and missing tools, components and facilities

3.6 Estimated budget

Item	Vendor	Model	Cost
Star, sun or horizon tracker	Swedish Space Corporation	Fine Sun Sensor	$24,000
Reaction wheels			$20,000 (est.)
Magnetometer	MEDA	TAM-2	$26,500
Magnetic torquers			$1,500 (est.)
Solar cells			$300 (est.)
Radio Polarizer			$1,000 (est.)

Control/Interfacing Electronics			$10,000 (est.)
Total			$83,300 (est.)

Table 3.6 Estimated GNC budget

Provided by University of Arizona: mentor and student hours for the project duration of two years:

Item	Equivalent Cost
133 Mentor hours @ $35	$4655
2750 Student hours @ $10	$27,500
Total	$32,155

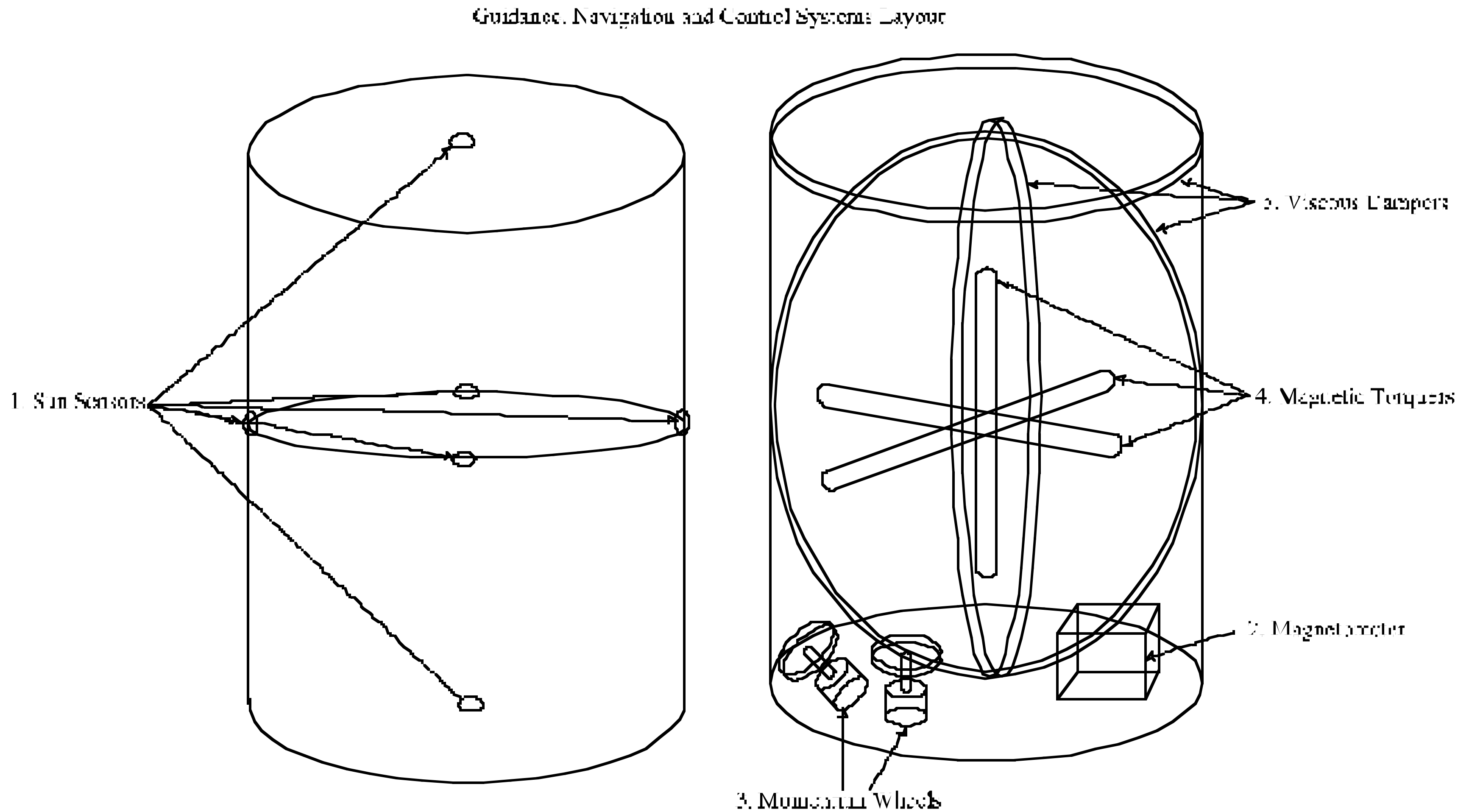


Figure 3.2 GNC subsystem systems layout

3.7 GNC Subsystem Schedule

3.7.1 Preliminary design

Prelim Design June 16 to October 30 1997 Based on 7 students working 10 hours a week on the GNC subsystem. PA: Pointing Accuracy, PD: Preliminary Design															
	6/16	**6/23**	**6/30**	**7/7**	**7/14**	**7/21**	**7/28**	**8/4**	**8/11**	**8/18**	**8/25**	**9/1**	**9/8**	**9/15**	**9/22**
1	PA: Space environment		PA: est. accuracy	PD: design dampers		PD: design solar cell system			PD: Model sensors			Model control	PD: analyze design	PD: Documentation	
2	PA: Space environment		PD: model space environment.				PD: Model sensors		PD: spec. controls	PD: analyze design			PD: analyze design	PD: Documentation	
3	PA: Spacecraft dynamics		PD: Setup simulation				PD: design star tracker		PD: spec. controls	PD: feasible 2 r.w.			PD: analyze design	PD: Documentation	
4	PA: Spacecraft dynamics		PD: Setup simulation				PD: Model dynamics			PD: analyze design			PD: analyze design	PD: Documentation	
5	PA: Sensors		PD: design torquers				PD: Model actuators		PD: spec. controls	PD: feasible 2 r.w.			PD: analyze design	PD: Documentation	
6	PA: Reaction wheels		PD: design torquers				PD: Model actuators		PD: spec. controls	PD: feasible 2 r.w.			PD: analyze design	PD: Documentation	
7	PD: Polarized radio transmission								PD: Design reaction wheel amplifiers					PD: Documentation	

Table 3.7 GNC Preliminary Design Schedule

3.7.2 Detailed Design: October 9 - December 5 1997

3.7.3 Fabrication: January 5 - July 28 1998

3.7.4 Testing and Calibration: May 18 - August 28 1998

3.7.5 Integration: August 31 1998- February 26 1999

3.7.6 Final Testing and Calibration: March 1 - May 26 1999

3.8 Task List

3.8.1 Preliminary Design

Module	Task	Student hours	Mentor hours	Description
Space environment	Characterize the space environment	40	2	Describe globally Earth's magnetic field, Earth gravitational field, Make a list of possible disturbance torque's. Make a table: causes, change.
Spacecraft dynamics	Characterize uncertainties in spacecraft dynamics	40	2	Identify and characterize uncertainties of the spacecraft. Internal t parts, mechanical battery. Model uncertainties, center of gravity no
Sensors	Characterize sensors	20	1	Describe globally sun sensors, magnetometers, star trackers. Identi info catalogs etc. Make a table for each sensor: vendor type # accu power requirements, "update rate", comments. Try to identify influ accuracy.
Actuators	Characterize reaction wheels	20	1	Describe globally working reaction wheels. Identify vendors, get i Make table vendor, type #, rate torque, max speed, price, weight, c
Analysis	Estimate pointing accuracy	10	1	Using the gathered information from the previous tasks make an es accuracy.
Sensors	Preliminary design star tracker	40	2	In corporation with the SCI team describe how the science instrum Address mechanical, electrical, software design issues. Characteri rate, accuracy etc. (dimensions weight etc.). Consider alternative:
	Preliminary design solar cells	60	3	Make a principal sketch of the system. Describe the principal work algorithms. Identify vendors of small suitable solar cells. Make tab relevant info. Corporate with the PGD team to determine how the an estimate of the achievable accuracy, power requirements etc.
	Polarized radio transmission	80	4	Literature research, describe principle working of system. Identify Work with the TTC team
Actuators	Preliminary design magnetic torquers	80	4	Describe fundamental principles. Make estimate of needed torque momentum dumping requirements. Make specification for the torq mechanical design and estimate achievable torque's. Identify critic requirements, efficiency. Corporate with MSS team for available s
	Preliminary design viscous dampers	20	1	Describe fundamental principles. Make preliminary mechanical de damping. Identify critical design parameters. Corporate with MSS
	Preliminary design reaction wheel amplifiers	60	3	Find possible vendors of amplifiers that can be used for the reactio recapturing of the energy when the wheels slow down. Make a ele Work with the PGD team on this. They have the same problem wit
Control algorithm	Detailed specification controls	80	4	Find overview papers about spacecraft attitude control, books etc. causes (recovery after subsystem failure, normal disturbances etc. which sensors to use for each phase. Identify performance criteria compared.
	Feasibility study two reaction wheels	60	3	Make overview of literature (papers, books) about algorithms on t approach to control problem. Design and simulate controller for sir especially for the axis perpendicular to the actuator axes.
Analysis	Setup simulation	80	4	Search for existing software models etc. Make a general lay out of should be written, using simulation packages. What do NASA have (power consumption, stability, pointing accuracy, overall algorithm
	Model space environment	40	2	Find/make mathematical model of the space environment. Disturba planets? What do we need for modeling sensors?
	Model sensor	50	3	Find/make model of each sensor that we use. Include characteristi dynamics
	Model actuators	40	2	Find/make model of each actuator. Include actuator saturation, nor consumption etc.
	Model spacecraft dynamics	40	2	Model a rigid spacecraft. Include gravity gradient, internal disturb

				etc.
	Model control	20	1	Model control law, supervisor system etc.
	Analyze preliminary design	60	3	Run simulations. Estimate performance whole system. Spot weak p
Document-ation	Documentation preliminary design	100	5	Make documentation of the preliminary design. Include drawings c become a reference work.

Table 3.8 GNC Preliminary Design Tasks

3.8.2 Detailed Design

Module	Task	Student hours	Mentor hours	Description
Sensors	Detailed design star tracker	100	5	Make detailed mechanical drawings. Choose materials etc. Make circuit diagram and PC Design software algorithms.
	Detailed design solar cells	50	3	Design with PGD team the necessary electronics. Design the software algorithms and w
	Polarized radio transmission	100	5	Design the electronics and the algorithms with the TTC team
Actuators	Detailed design magnetic torquers	80	4	Make detailed mechanical design. Choose material, dimensions etc. Make detailed desig circuit diagrams, PCB lay outs etc.
	Detailed design viscous dampers	40	2	Make detailed mechanical design of damper. Choose materials, dimensions etc.
	Detailed design reaction wheel amplifiers	80	4	Make design of the steering amplifiers and the electronics required for distributing the e Choose components, make circuit diagrams, PCB layouts etc.
Control algorithm	Detailed design control software	70	4	Detailed design of the super visor software. Detailed design of control algorithms for ea
Analysis	Modeling subsystems	40	2	Update and refine model of the space environment, sensor, actuators, spacecraft dynami Do we need to model the flexibility of the spacecraft.
	Analyze detailed design	80	4	Run simulations. Check performance whole system. Are the specifications met? So not a
Document -ation	Documentation detailed design	100	5	Make documentation of the detailed design. Include detailed drawings of the sub system of the subsystems.

Table 3.9 GNC Detailed Design Tasks

3.8.3 Fabrication

Module	Task	Student hours	Mentor hours	Description
Sensors	star tracker	200	10	Construct star tracker parts. Order components etc. Work with the SCI team
	solar cell	40	2	If necessary order small solar cells. Otherwise order electronics components. Fabric electronics.
	Polarized radio transmission	80	4	Order electronic parts, fabricate PCBs. Assemble electronics
	Magnetometer, sun sensor	10	1	Order magnetometer and sun sensor
Actuators	magnetic torquers	150	8	Fabricate magnetic torquers. Order materials and assemble. Order electronic compo
	viscous dampers	40	2	Fabricate the dampers
	reaction wheel amplifiers	100	5	Order reaction wheels. Order amplifiers or build them.

Table 3.10 GNC Fabrication Tasks

3.8.4 Testing and Calibration

Module	Task	Student hours	Mentor hours	Description	Skills, equipment
Sensors	star tracker	50	1	test star tracker hardware	
	solar cell	50	1	test solar cell system hardware	
	Polarized radio transmission	50	1	test polarized radio transmission	

	Magnetometer, sun sensor	50	1	test magnetometer, sun sensor etc.	
Actuators	magnetic torquers	50	1	Test electronics, torquers	
	viscous dampers	50	1		
	reaction wheel	50	1	Test the reaction wheels and amplifiers.	

Table 3.11 GNC Testing and Calibration Tasks

3.8.5 Integration

Module	Task	Student hours	Mentor hours	Description	Skills, equipment
All modules	integration	300	15	Mount all sensors, hardware etc. in satellite.	

Table 3.12 GNC Integration tasks

3.8.6 Final Testing and Calibration

Module	Task	Student hours	Mentor hours	Description	Skills, equipment
All modules	testing and calibration	300	15	Perform final test and calibration of the GNC subsystem	

Table 3.13 GNC Final Testing and Calibration Tasks

4. Power Generation and Distribution

4.1 Goals and Specifications:

Our Goal is to supply the Satellite with the power needed for operation and to carry out the scientific mission. Our secondary goal is to prove new energy technologies for Space. Thereby, increasing their Technology Readiness Levels. This would raise them from their current levels to a reliable eight. This includes the flywheel experiment and possibly new experimental Solar cells from a subsidiary of TEP – Global Solar.

Our specifications are very flexible and will be modified to best meet the needs of the satellite. Currently, we are planning on supplying all other subsystems with power from a 28V Bus (which is standard in small spacecraft).

Furthermore, we will supply the satellite with power ranging from 50W to 80W. We will also provide data to the Data and Command Handling Team on the solar cells, batteries and distribution from sensors through a serial data port.

4.2 Design Approach:

Figure 4.1 presents a typical satellite functional block diagram that identifies the major elements involved in the power subsystem. A substantial variety of options exist within each of these elements. Table 2.1 identifies the options most likely to be considered for the power subsystem.

We have subdivided the team into four sub units: Generation, Energy Storage, Flywheel, and Distribution. We will be using a 'black box' approach that is common to engineering. All sub units will only worry about what is in their black box and their interface to the outside world. In essence the Distribution sub team is our interface to the outside world, and the rest of the team can just worry about internal issues and supplying the distribution team with one voltage and power.

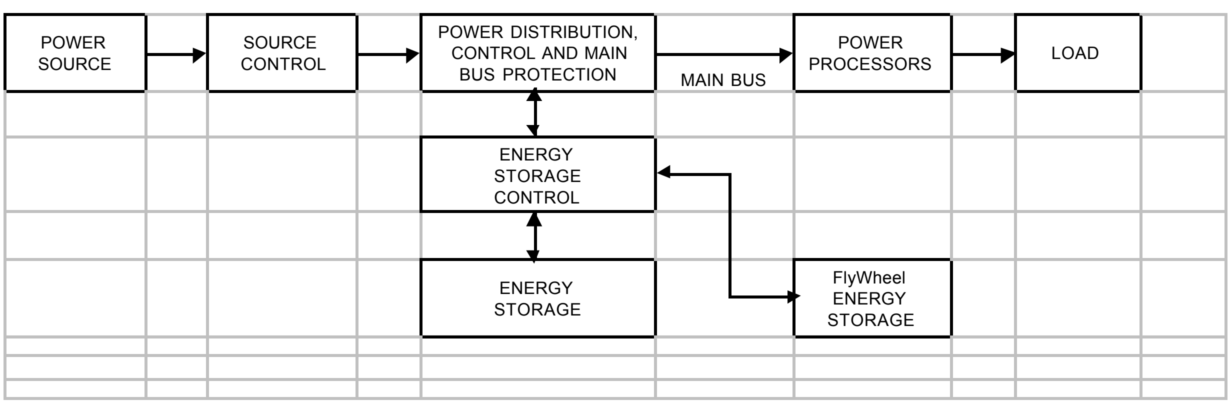


Figure 4.1 PGD Block Diagram

4.2.1 Division of Labor

The distribution team will be responsible for designing the necessary converters for those that need voltages and at different levels, as well as working with the DCH team to provide a way to control which subsystems get power.

The generation sub-team will be responsible for obtaining the solar cells and finding the best way to use them to meet our power distribution needs. They will also develop ways to measure the efficiency and productivity of the solar cells. This would be especially needful if we obtain an R&D agreement with some company such as Global Solar.

The primary energy storage team will research batteries and obtain the best batteries for our mission. They will also configure an appropriate backup solution. Additionally, they will be responsible for providing the control mechanisms to switch between storing energy in the flywheel and the battery, as well as feeding data to DCH on how much energy is stored in the battery.

The flywheel sub-team will be responsible for building a small flywheel set, designing the experiment and a way to document it. They will also work in conjunction with the GNC team to ensure that the flywheels will not adversely affect the stability of the craft.

4.2.2 Fabrication Approach

Ideally, we will not have to fabricate much of anything, other than the flywheels. We should be able to appeal to industry for some excellent space rated batteries. The solar cells will either be available commercially or will come from an R&D agreement, i.e. Global Solar. Currently, one of our team members is working with SatCon gaining experience on how to design and build a flywheel.

We will however need to design and fabricate a circuit board that will control the power switching and data gathering on our subsystem. We hope to be able to use the facilities of the ECE dept. of University of Arizona. They have some integrated circuit labs.

4.3 Schedule

Procuring Alliances w/ Global Solar & Satcon	19 May 11 July 1997

4.3.1 Preliminary Design — 16 June – Oct 3 1997

Generation
Primary Storage
Storage Control
Storage - Flywheel
Distribution (Discovering Power needs)
Deployment of Solar Cells

Table 4.1 Post-Preliminary Design Schedule	
Detailed Design	9 Oct – 5 December 1997
Critical Design Review	8-10 December 1997
Fabricate	Jan – Aug 1998

Test and Calibrate	18 May – July 1998
Integrate	31 Aug – 26 Feb 1999
Final testing and Calibration	Feb – May 1999
Ready for Delivery	5 June 1999

4.3.2 Flywheel subteam schedule

Table 4.2 Flywheel subteam schedule	
Design of Fiberglass frame	1 Aug 2 Sept 1997
Array Drive Unit(if needed)	31 July- 18 Sept 997
Momentum Wheel design	28 August- 19 September 1997
Magnets (samarium cobalt? Ceramic?)	12 October- 2 November 1997
Fiber Epoxy Rotor design	20 September- 11 October 1997
Motor Generator design	29 September 10 December 1997

As other subteam scheduled become available we will make them known.

4.4 Mission Tools

Table 4.3 Mission Tools					
Labs	Equipment			Software	
TEP	Possibility	O-scope	ECE	PSPICE	Have it
ECE & AME	Possible	Breadboards	ECE	Microstation	Have it
Vacuum Thermal Chamber	Unknown	Batteries	TEP	Other AutoCad (ProE)	School may have it
Solar Tester (like Phillips Laboratory)	Unknown	Solar Arrays	TEP	Simulator of Orbits	Unknown
SatCon	Good possibility	Circuit Elements	ECE		

4.5 Estimated Budget

Table 4.4 Estimated Budget				
What	Cost/item	Quantity	Quantity	Total
Student support	$6/hr	8 students	300 hrs each	$14400
Mentor	$30	3 mentors	100 hrs each	$9000
Equipment Acquisition				$3000
Operational				$2000
TOTAL				$28400

5. Data and Command Handling

5.1 Introduction

The purpose of the Data and Command Handling Team is to design and build the onboard computer for the satellite. The system we build will be responsible for several operations, the greatest of which is interfacing with and controlling the scientific instrumentation. This involves the interpretation of all commands received via the ground station and the subsequent translation into the corresponding machine code for each of the scientific subsystems. It will also be responsible for detecting and correcting errors involving any of the peripheral subsystems as well as any software or hardware errors from within the computer itself. Finally, it will format and compress the scientific data and transmit it along with housekeeping data to the ground station via our onboard radio link.

Since the satellite will only be accessible to us for a maximum of about thirteen minutes during each orbit, these functions will need to be largely autonomous. The onboard computer will need to be able to carry out a set of timed, pre-defined instructions which must be implemented without the consultation or supervision of the ground station. With this and other factors in mind, we decided to implement the Intel 80C186EC Processor as the system's CPU. The 80C186EC is a 25 Mhz embedded processor which is very similar to its predecessor, the 8086, with the addition of extended peripheral handling capabilities. We will utilize these capabilities by mapping them to the scientific subsystems on the satellite. Another very important reason for choosing this older processor is its exceptional radiation tolerance of 8 Krads (3 Krads higher than the accepted minimum).

5.2 Hardware

Along with the 80C186EC CPU, the onboard computer will need to have a heap of memory in which to store data. This will be accomplished by using anywhere from 1 to 3 12Meg SRAM cards. The CPU can address up to 1 Mbyte of physical SRAM. However, if the science team requires additional storage, a paging device can be implemented to allow up to 32 Mbytes of SRAM or more. All custom logic will be implemented on two Actel Field Programmable Gate Array (FPGA) chips and all software will be contained within rad-hard EPROMS.

As for data handling, all scientific and command information which the system must send or receive will be routed to and from radio modems. The modem(s) will most likely use an RS-232 interface for information exchange. Since data will go both directions through this interface, we will utilize a serial connection, one of three addressable by the 80C186EC. If the serial port's data rate proves itself too slow, we can easily switch to a parallel port interface.

As for managing the thermal output of the onboard computer, the structural team does not feel that there will be enough heat to warrant any concern, but we will consider the addition of heat shielding anyway. As for the physical space it will use on the satellite, we expect our computer to use around 1300 CCs, where most of this space will be taken up by the SRAM array. If we allow for the addition of computer options and thermal shielding for the system, we will utilize approximately 7500 CCs of space.

5.3 Software (Operating System)

The tasks we will lay out warrant a multi-tasking operating system so that the computer can perform several operations concurrently. This necessity is obvious in situations where the computer needs to run its error checking and systems monitoring routines at the same time scientific data is being collected. In addition, the operating system's task list should be able to interpret all command requests, such as where to place the data, and how to send out a command to the right subsystem. Bektek's SCOS is a multi-tasking operating system. It is small and has flown on many previously successful amateur satellites. We would prefer to purchase a commercial OS as opposed to custom designing our own due to the fact that we don't have the resources at this time. However, should funding become a problem, the software side of our team will endeavor to program this multi-tasking real time operating system along with our custom command set.

5.4 Error Handling

There are two main types of computer systems error: hard errors and soft errors. Soft errors are temporary disruptions in the normal operation of the system, whereas hard errors are those which cause permanent damage. The former is usually caused by some internal exception caused by a software error, where the latter is usually caused by exposure to high energy radiation such as alpha particles or cosmic rays.

In order to correct soft errors, we must first detect them. To do this, we will implement two strategies. For the first we will employ the use of the 80C186EC's inherent watchdog timers which will reset the whole system in the event that a critical command isn't processed within a set time limit. For the second, Error Detection And Correction (EDAC) circuitry will be implemented alongside the SRAM array to minimize the chance of a flipped bit error as well as to protect the array itself. Errors within subsystem communication can be detected via Hamming codes and dealt with by prompting the system to re-send the corrupted information. We also need to ensure that false commands will not be executed, and guarantee the integrity of the data.

The 80C186EC has inherent exception handling characteristics which we will utilize for the satellite. In the event that the CPU or other subsystem incurs an unrecoverable soft error, the system will call an exception table which will deal with the problem (usually by resetting the subsystem).

As for hard errors, in the case that an ionizing cosmic ray creates a direct connection between Vcc and ground, the rush of current can cause permanent damage to the chip. By attaching series resistances to the power pins of the IC's, in many cases we will be able to prevent hard errors of this kind. In the case that a system's wide hard error occurs, although unlikely, the system will have the option to perform a hard boot.

5.5 Interface with Scientific Subsystems

Apart from the auto-induced housekeeping chores such as EDAC, the onboard computer will need to interface and control the rest of the satellite. Current plans for the scientific experiment involve a 12-bit CCD. The CCD contains an inherent analog to digital converter, thus the output will be digital. We need to allot a section of SRAM for the purpose of storing raw images fresh from the CCD so that they can be compressed before they're formally stored for later transmission. Thus, a frame buffer will be implemented and will need only be around 640K. While the Frame Buffer should easily be able to interface with the CCD via either an RS-232 or RS-422 serial connector, the CCD itself needs to be sent commands such as "expose for 1/8 of a second at 18:30:23." Separate commands will be used for orienting and manipulating the camera, but all command information will be transmitted along the same connection as the data output.

We will incorporate start, end, and error bits into each command in order to control the flow of data and warn us about errors. If the CCD were to fail (error bit = 1), the exception handler would be switched on and would end the current transmission and reset it. Similar message bits would be used for all other scientific instrumentation. A “clear-to-send” (CTS) signal will be utilized so that the computer will know when to dump all its data from the SRAM array to the modem. After completing the download of each image and its accompanying supplementary information, a “done” signal will be added to the end of the data stream. Obviously, actual commands are far from being realized, but it is our hope to be able to use the serial interface for both input and output, receiving data from the experiment and commanding the device.

Each raw CCD image will be approximately 24 KB (128 x 128 x 12 bits), and with a Jpeg converter we can reduce each of them even further by a factor of around 5 to 1. Thus, even with only 1 Meg of SRAM we can store at least 100 pictures along with the housekeeping data. This jpeg converter can be in the form of a software executable or a Zoran Jpeg hardware encoding device. We would prefer the latter as it would be less taxing on the processor. The Frame Buffer will be capable of storing around 40 raw images, so as long as our compression/storage rate for the image data exceeds the rate at which it's created, we'll be fine. However, due to the fact that science team figures are not yet final, we have addressed the problem of adding additional SRAM.

5.6 System Power Management

In order to manage the satellite’s power consumption, we need to be constantly aware of the state of the batteries when they are recharging. The onboard computer needs to monitor whether the batteries are fully charged, or in the process of being charged and whether enough power is available to run non-critical processes. The communication can be as simple as a “charging ok” byte string, and a numerical string indicating the amount of current power and its rate of increase.

5.7 Space Craft Orientation and Control

The only housekeeping chore left is guidance and navigation. Apart from controlling the scientific instrumentation, this will be the most complicated task. The science team’s CCD does not provide us with the locations of what it’s photographing. Therefore, if this is to be known, the guidance system will have to contain an interface which continuously reports the location of the satellite relative to the earth. Combining this with CCD orientation data, a stamp will be added to each image which will tell us the time it was taken and its location on the earth’s surface. We will also need to have an interface between the onboard computer and the guidance system so that we can orient the satellite manually.

We would prefer that the guidance system have some sort of autonomous processor, independent of the onboard computer as it would use up part of our valuable processing power. This system must also be capable of communicating with the onboard computer so that it can service manual commands and the onboard computer can receive warning and error information.

An integral part of our design plan involves being able to adapt to the specifications of the other design teams. Our position is unique in that our team, more than any other team, must work with and adapt to the designs of all the individual subsystems. To minimize major design changes, we have chosen a basic hardware system that is well accepted, robust, and can easily be modified to accommodate future changes.

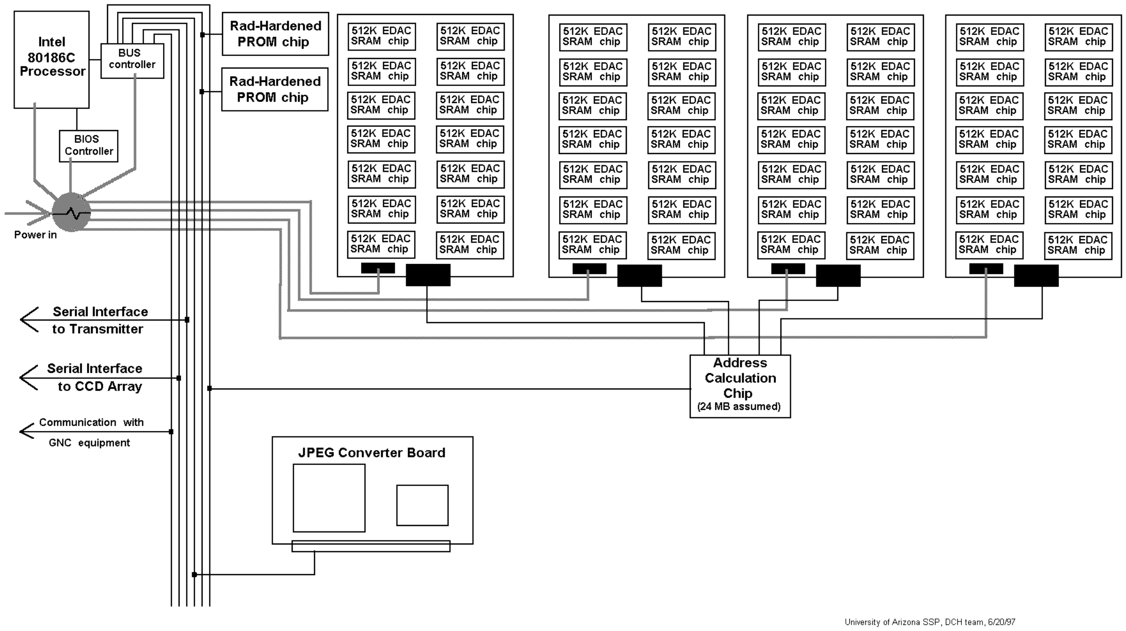


Figure 5.1 Simplified Internal Data Path Diagram

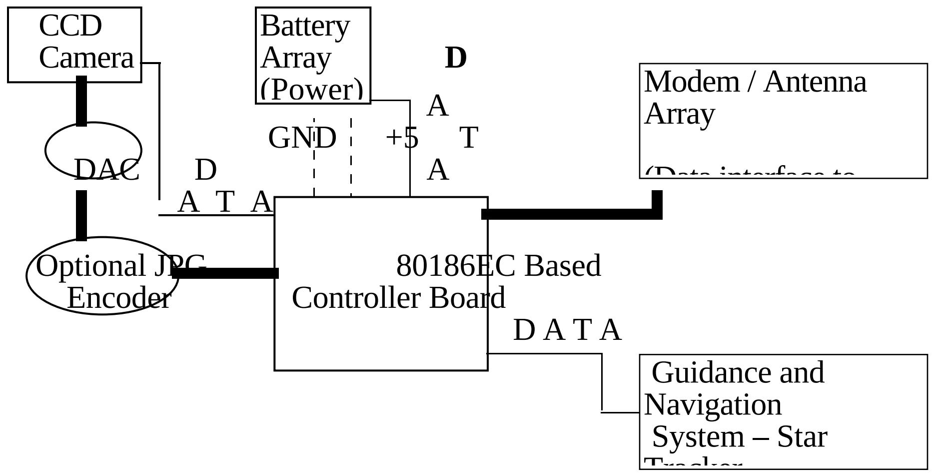


Figure 5.2 Simplified External Data Path Diagram

The following is a list of missing and available skills, utilities, and facilities that will be needed in the design and testing of the computer system.

Special tools:

- EEPROM writer
- FPGA burner
- Facilities for producing a multi-layer printed circuit board 80186EC design schematics (pin out diagrams, etc)

Special Skills:

- Skills required to produce a multi-layer printed circuit board
- An expert in 80186 interfacing

Materials: (We will assume to build four computer systems, for testing and debugging purposes)

Hardware:

- Intel 80C186 processors
- blank circuit boards
- serial interface boards/chips
- raw CCD to JPEG converter card OR possibly just the converter chips
- EEPROMs for preliminary design
- rad-hardened PROMs for final system
- 3 12 MB EDAC'ed SRAM array cards
- Non-EDAC'ed SRAM

Software:

- Bektek Satellite OS/other OS compatible for x86 architecture
- third party embedded system library for 80C186 processor
- Hardware Design Software Suite (CAD, virtual circuit

- software, etc.)
- Ansi C Programming environment and tools Misc. electronic components.

Table 5.1 DCH Schedule	
June 20	Turn in Final Proposal
June 30	Correlate with other teams to determine needs.
July 4	Determine Operating System to be used
August 15	Determine software to be programmed (i.e. commands needed, format for the data, etc.) Finalize supporting hardware (shielding, etc.)
September 5	Finalize hardware requirements
September 15	Find all hardware required
October 5	Finish details of design
October 6	Submit project for final design review

Table 5.2 DCH Estimated Budget	
Student pay: $6/hr, 3 paid students, 10 hrs/wk, 50 wks	$9,000
Mentor pay: $75/hr, 4 mentors, 4 hrs/wk, 50 wks	$60,000
Computer hardware x 4 (see materials for components)	$6,000
Bektek Operating System (other operating system would cost $0 to a few hundred)	$25,000
Embedded system library (most likely freeware)	$0
Hardware design software tools:	$25,000
Programming software (ie, Visual C++):	$250
Total	$125,250

As this is an educational and scientific endeavor, most time will be donated, bringing the budget down by over half.

6. Tracking, Telemetry and Control

6.1 Goals and Specifications

6.1.1 Introduction

L-band (1.0 – 2.0 GHz), S-band (2.0 – 4.0 GHz) and X-band (8.0 – 12.0) communications have been researched in depth, and have seen a great deal of use in both telemetry and radar mapping technologies. The Alaska SAR (Synthetic Aperture Radar) Facility employs x-band frequencies as its surface-mapping instrument. NASA uses x-band transmission for communication with its deep space probes.

The design of the telemetry link between the spacecraft and the ground station must address several design issues. They include:

- Antenna selection
- System temperatures and receiver G/T ratios
- Bit rates
- Link budgets
- E_b/N_o and C/N_o ratios
- Bit error rates
- Losses associated with uplink and downlink
- Data transfer protocol
- Groundstation implementation

This proposal examines several frequency ranges and considers them based on data rates achievable. A final decision on frequency of operation can then be based on results that follow.

6.2 Design Approach

6.2.1 Frequency Allocation

The first consideration in the design of the telemetry link between the spacecraft and the ground station is allocating a frequency range. This is done with careful examination of the Federal Communications Commission (FCC) guidelines for both frequency allocation and bandwidth [1]. Several frequency ranges are considered, with a final decision being based upon required data rates for the science instruments.

Since the satellite we are building will be launched via the Space Shuttle, we are planning for a Low Earth Orbit (LEO) at about 22 – 23 degrees inclination. These orbits typically have a period of 90-100 minutes. Based on this information, we can assume between 15 and 16 orbits per day. The average pass time of these types of orbits is typically 8-12 minutes, depending on the maximum elevation of the satellite during the pass. However, only about 80-85% of these orbits will be useable, resulting in only about 12 useable orbits and only 96 - 144 total minutes of data gathering time per day.

Because digital data is being transmitted, a relatively high data rate will be required in order to transmit all data within the 7-10 minute window available during each pass of the spacecraft. Table 1 shows the specifications for the telemetering system. These specifications are discussed in detail below.

Bandwidth requirements can be determined from [1], and are expected to range from 1 to 30 MHz, depending on the frequency range chosen. This bandwidth must comply with FCC regulations for digital transmission.

Table 6.1 TTC Specifications

Component	
Spacecraft transmitter power	1.2 Watts (6 Watts in, with assumed 20% efficiency)
Spacecraft antenna gain	4 dBi (Omni-directional)
Ground station transmitter power	30 Watts
Ground station antenna gain	30 dBi (parabolic reflector)
Nominal distance from spacecraft to ground station	250 km
Data Rate	Variable
Receiver bandwidth	TBD
Modulation	QPSK
Required Bit Error Rate (QPSK)	10^{-9} down-link, 10^{-6} up-link
Up-link frequency	1.2 GHz
Down-link frequency	2.4 GHz
Spacecraft System Temperature	~300 K
Ground Station System Temp.	~150 K

6.2.2 Antenna Selection

Antenna selection is especially important for the spacecraft design, where size and beam-width are of primary concern. The proposed design calls for two hemispherically omni-directional patch antennae for up- and downlink, respectively. Obviously, size is considerably reduced as the frequency of operation increases.

There are several advantages to using an omni-directional antenna. Little or no pointing of the antenna is required, significantly reducing the overall spacecraft system complexity. The transmission wave can be circularly polarized to eliminate the effects that craft rotation could have on a linearly polarized wave. Also, patch antennae are virtually massless, extremely thin, and can be easily mounted in conformance to the outer hull of the craft. Additionally, there are no moving parts. The main disadvantage is that there is a considerable loss of gain. However, as calculations below will show, this has little consequence for the link between spacecraft and ground.

The ground station antenna is chosen based on the requirement to meet specified E_b/N_o, G/T_{sys}, and C/N_o ratios. A parabolic reflector is the preferred choice because of its availability, high gain, and ease of pointing. However, the use of an array of crossed YAGI antennae or a helical antenna would allow us to use the UA Amateur Radio Club's pre-existing tracking antenna mount.

Other antennae may be added to accommodate AMSAT integration. We are thinking of adding a 2m-up/70cm-down voice transponder. To backup the Guidance & Navigation team's ability to measure the spin rate of the craft, we plan to add a Morse beacon, signaling housekeeping data on a linearly polarized wave. The spin of the wave will be proportional to the spin of the craft, and this can be measured.

6.2.3 Bit Rates

The downlink data rate is chosen based on requirements specified by the various science experiments on-board the spacecraft. The uplink data rate is chosen to be low (~1 KBPS) because the only data needing to be transmitted from the ground station to the spacecraft is that information that performs synchronization, control commands, and handshaking.

Bit error rates are chosen in a similar way. A lower bit error rate is required for the downlink due to the importance of the data and the large data rate. The uplink requires a higher bit error rate due to the lower data rate and because of cost considerations.

6.2.4 System Temperature

To compute system temperatures, some assumptions are made. Since little is known about the receivers on either the spacecraft or the ground station, we have assumed the majority of system temperature to be introduced by the antenna, the antenna feed, and the low noise amplifier (LNA) (if the reference plane is chosen as the input to the LNA). This assumption is shown to be valid in [1], [2]. Therefore,

$$T_{sys,r} \approx (T_{ant} + T_{feed})G_{feed} + T_{LNA} \tag{1}$$

where

$$T_{LNA} = (NF - 1)T_p \tag{2}$$

NF = Noise Figure

T_p = Physical Temperature of LNA

T_{feed} = Temperature of antenna feed

G_{feed} = Gain of antenna feed

T_{ant} = Antenna temperature

A good LNA has a noise figure of around 1 dB. T_p is chosen based on the temperature of the receiver circuitry. For well-designed space systems, temperatures on the order of 40 K are easily achieved. Cryogenic cooling can produce temperatures on the order of a few Kelvin.

Antenna temperature must be divided into uplink and downlink. For the downlink (spacecraft to ground station), the receiver antenna is the reflector on the ground station. Depending on whether the antenna is pointed low on the horizon or close to zenith, the antenna temperature can vary significantly. For worst case (antenna pointed close to the horizon), it is seen from [1] that that antenna temperature is 120 K. 150 K is chosen based on expected feed temperature, feed gain, and LNA temperature.

For the uplink, the spacecraft will ‘see’ both the earth’s atmosphere, which has a temperature of approximately 290 K, and the earth’s surface, with an average temperature of 281 K, and attaining a maximum of 310 K.

6.2.5 $G/_{T_{sys}}$, E_b/N_o, C/N_o Ratios

Once the system temperature is known, receiver gain-to-system temperature ratios, carrier-to-noise ratios, and energy per bit-to-noise ratios can be calculated. This will aid in determining bit rates and the effects of frequency allocation on the link budget.

The above ratios are calculated from [2] as

$$[C/N_o] = [EIRP] - [L_s] + [G_r/T_{sys,r}] - [k] - [AML] - [AA] - [L_p] \tag{3}$$

$$[E_b/N_o] = [C/N_o] - [R_b]$$

(4)

where $[EIRP]$ = equivalent isotropic radiated power, dBW

$[G_r/T_{sys}]$ = Receiver antenna gain-to-system temperature ratio, dB/K

$[L_s]$ = Free-space spreading loss, dB

$[k]$ = Boltzman's constant, -228.6 dBW/Hz-K

$[AML]$ = Antenna misalignment loss, dB

$[AA]$ = Atmospheric absorption and attenuation loss, dB

$[L_p]$ = Polarization mismatch loss, dB

$[R_b]$ = Data rate, dBHz

In (3), the loss terms represent losses thought pertinent in the design of the telemetry link. The three terms considered are:

1. AML, which represents possible losses associated with antenna misalignment.
2. AA, representing absorption and attenuation losses due to the atmosphere. This includes any scintillation effects.
3. L_p, which accounts for any polarization mismatches between the two antennas.

Other losses exist, and not all can be accounted for with this proposal. One other loss that can be considered is rain. Attenuation of radio waves through rain clouds is extremely frequency dependent. Empirical data exists [1], and the results can be used to estimate the amount of power lost due to propagation through a rainstorm.

A link margin is introduced to account for (hopefully) other, relatively unpredictable, losses. The EIRP of the downlink is calculated as

$$[EIRP] = 10\log P_t + G_t(dB) = 10\log 1.2 + 4dBi = 4.79dBW$$

and for the uplink as:

$$[EIRP] = 10\log P_t + G_t(dB) = 10\log 30 + 30dBi = 44.77dBW$$

The free-space spreading loss, L_s, for a link distance R, is calculated as

$$[L_S] = 10\log\left[\frac{4\pi R}{\lambda}\right]^2$$

Table 6.2 and Table 6.3 show link budgets for the uplink and downlink, respectively, for a frequency of operation of approximately 2.5 GHz. The value of E_b/N_o required is found for QPSK modulation from [1]. Quadrature Phase Shift Keying is chosen because of its bandwidth efficiency and performance versus other modulation schemes.

In Table 6.3, the data rate possible is calculated as

$$[R_{b,possible}] = [C/N_o] - margin(dB) - [E_b/N_o]_{required}$$

Table 6.2 Ground station-to-spacecraft uplink power budget (worst case) - 2.5 GHz

Component	

EIRP	44.77 dBW
Free Space Loss (200 km)	143.9 dBW
Polarization Loss	0.5 dB
Antenna Misalignment Loss	1.5 dB
Atmospheric Attenuation	3 dB
Loss due to rain (large cloud burst)	1.5 dB
Boltzman's Constant	-228.6 dBW/Hz-K
Receiver G/T	-21.62 dB/K
C/N_o Available	101.34 dB
Data Rate	1 Kbps = 3 dBHz
E_b/N_o available	98.34 dB
E_b/N_o Required	10 dB
Margin	88.34 dB

Table 6.3 Spacecraft-to-ground station downlink power budget (worst case) - 2.5 GHz

Component	
EIRP	4.79 dBW
Free Space Loss (200 km)	143.9 dBW
Polarization Loss	0.5 dB
Antenna Misalignment Loss	1.5 dB
Atmospheric Attenuation	3 dB
Loss due to rain (large cloud burst)	1.5 dB
Boltzman's Constant	-228.6 dBW/Hz-K
Receiver G/T	8.24 dB/K
C/N_o Available	92.73 dB
E_b/N_o Required	13 dB
Margin	10 dB
Data rate possible to achieve link margin of 10 dB	69.73 dBHz = 9.40 Mb/sec

Similar calculations demonstrate that the data rate achievable decreases dramatically with increasing frequency. This is due in large part to the increased free space spreading loss and the extreme frequency dependency of rain attenuation. Note that if the requirement for radio wave propagation through rain were relaxed (i.e., assume a small cloud burst or no rain at all), then the data rate possible at 30 GHz would be 152 kb/sec (assuming no rain). Thus, if 30 GHz were chosen as the frequency of operation, the only way to receive data during a large rainstorm would be to back off the data rate. Otherwise, data would not be collected during an orbital pass where a large rainstorm interfered.

The final frequency of operation chosen will depend on the data rates needed by the science instruments. Based on preliminary reports on required data rates, it is proposed that either 2.5 GHz or 8 GHz be chosen. These frequencies will ensure high data rate operation even when propagating through large rainstorms. These data rates, in combination with good compression techniques and a packet design employing error correction and

One argument for using 2.4 GHz as the operating frequency is that is an amateur radio band. Additionally, this is about the highest frequency you can use and still have commercially available parts at a reasonable price. This band of frequencies can be used by anyone with a HAM license. Operating a satellite on amateur frequencies would undoubtedly be of interest to AMSAT, and we could solicit both their help and expertise. If 2.5 GHz is chosen as the operating frequency, a relationship with AMSAT will need to be established.

6.2.6 Data transfer protocol

The communication protocol will be custom-designed, but based upon existing schemes. Transmissions will be made in discrete packets with the option of request a re-transmission from either end in the case of a corrupted packet. The overall organization of each packet, as shown in Figure 6.1, includes a packet frame, time stamp, housekeeping data, science data, replica data and a checksum. With such high data-transfer rates, we can even explore the use of replica data within each packet, to better ensure a valid packet each pulse..

General Packet Structure

Frame Header	Auxiliary Data: Original	Auxiliary Data: Replica	CRC

Figure 6.1 General Packet Structure

6.2.7 Groundstation

Once data has been decoded, it gets split into two components: science and housekeeping data. The science team will specify anything that needs to be done to its data before it gets stored. Once processed, this data will be sent to the science database for later processing and retrieval via a World-Wide-Web server. Housekeeping data gets pre-processed before being stored, checking for warning flags in critical areas of the various subsystems and the science payload aboard the craft. The pre-processor can check for critical flags set aboard the craft and then sent down to the Groundstation, but it can also check the incoming data against stored data for trending analysis, looking for more subtle problems. The exact nature of the system checks will be mandated by the final design of the entire craft. When a serious or potentially serious problem is detected, the computer will activate the alphanumeric paging system via an ordinary 14.4Kbps modem and a subscription to a pager service, sending a pre-specified string of text.

All incoming data gets stored in a database. This database is run by a separate computer, which also runs a WWW server. Our goal is to disseminate the downloaded satellite information as quickly as possible via the World Wide Web. The computer selected for this task will be comparable to the command computer, but with more hard disk storage and more RAM. Storage space and ability to be a server are the critical issues with this computer. We estimate that a 100 MHz Pentium with 32MB RAM, a 5GB hard disk drive, and a 7GB tape drive should be sufficient. These figures are, again, largely dependent upon the needs of the science payload. The large tape drive will be necessary to allow archival storage of an unspecified amount of data. This computer must also have an Ethernet card, and we will require an Ethernet Hub and a T1 connection to the Internet to complete the network. The operating system to be used would most likely be Linux for the control Computer, due to its customizability and low-level nature, and Windows NT for the Database computer due to software availability and ease of setup. Many high-power databases are available for Windows NT, and the 4.0 release comes with an Internet server built in. Additionally, Windows NT is a powerful and easy to implement network server.

Keeping with the Internet-based theme of the Student Satellite project, and to minimize the necessity for Groundstation-based operations, we propose the creation of a web site that dynamically retrieves and publishes imaging and housekeeping data from the database. Such systems can readily be implemented, and have highly configurable security options, enabling multi-tiered access to records. Other intriguing options made possibly by such a setup include the sending of regular automated status reports via e-mail, the set up of automated newsgroups for informational postings, and the possibility of remote manipulation of data and the remote control of the satellite. Tight security measures would have to be implemented in either case, but the possibility exists. Remotely accessing and manipulating data presents no regulatory problem, but there could be licensing and/or regulatory issues surrounding the remote control of the Satellite. This matter remains to be investigated.

6.2.8 Summary

A class of subsystems has been designed and considered. Link budgets have shown that high data rates are achievable for low to moderately high frequencies with high reliability. The final choice of frequency will depend on the availability of bandwidth, licensing considerations, cost, and data rates required by the science instruments. It is proposed that either a frequency range of 1.2 GHz or 2.4 GHz be considered. These frequencies have a wide use today, and parts are readily available at a reasonable cost.

The Groundstation technologies are well established. The Pentium chip has been out long enough to have its bugs worked out, and both Windows NT and Red Hat Linux are in their fourth full revision. The control interface of the tracking antenna is already owned by the U of A’s amateur radio club Groundstation, and will be in place by the end of this summer.

Our proposal builds upon well-proven technologies, customizing them for this project. The transponders and modems are the only components that have to be custom-designed and built. The other parts are commercially available off-the shelf (COTS) products. The software is a mixture of COTS products, homemade programs, and custom patching. The technologies we propose to use are already known to be reliable and effective.

We initially investigated using the Ka band for communications. The higher frequency could theoretically enable super-fast data transfer rates. Upon more investigations, however, we discovered that this band has a signal loss several orders of magnitude greater than the 8 GHz frequency when encountering atmospheric disturbances.   Moreover, the lower EHF bands have a sizable history of successful employment, whereas the Ka-band is relatively unexplored.

References

1. **Horan, S.,** *Introduction to PCM Telemetering Systems*, CRC Press, Boca Raton, 1993.
2. **Roody, D.,** *Satellite Communications,* Prentice Hall, Englewood Cliffs, 1989.

6.3 Fabrication Approach

Once designs have been carefully reviewed and critiqued, fabrication will begin in parallel along two main tracks. The Groundstation fabrication and the telemetry link fabrication. Students will choose to work on one or the other track.   One aspect to which we will pay close attention is getting frequent faculty, staff, and other knowledgeable persons’ technical advice. The satellite project at ASU encountered many pitfalls due to their lack of such support.

6.4 1997 Schedule

Table 6.4 TTC 1997 Schedule

June 1997
➢ Begin all designs of tracking, telemetry, and control systems: transponders, modems, and software. ➢ Have a group brainstorming session on current direction and ideas. Determine weak areas, and discuss design and fabrication approach. ➢ Volunteer or designate an AMSAT contact person and initiate correspondence.

July 1997

- Determine nature of relationship with AMSAT. Determine how they can help us with recommendations on equipment purchase, and with custom designs.
- Establish exact interface points between TT&C subsystems.
- Establish precise interface point with Data and Command Handling team.
- Prepare a block diagram of the design of the complete system.
- Establish system-level testing procedures and begin design of system simulation software.

August 1997

- Component and system research deadline. Team members should be familiar enough with their areas to initiate rudimentary designs where needed and to have a list with contact information and prices for components to be purchased or otherwise obtained.
- Initiate creation of detailed schematic diagrams and create precise specification charts of system components drawn up of the complete system according to our block diagram.

September 1997

October 1997

November 1997

- Complete preliminary schematic diagrams and specifications.
- Initiate preliminary system integration design

December 1997

- Begin constructing the necessary circuits for the two modems and two transponders needed for the satellite and Groundstation.
- Start the development of the software and ground station computer network.
    - Initiate system simulation testing.
    - Refine system design.
    - Complete system simulation testing.

6.5 Division of Labor

The tracking, telemetry and control subsystem consists of the following five main components: transceiver (satellite), transceiver (ground), terminal node controller, control computer and server. The work breakdown structure is as follows:

6.5.1 Satellite Transceiver:

Critical design:	Detailed design of a transceiver on the satellite that will effectively transfer and receive data at the satellite at a specified rate.
Funding:	Funding for the parts specified in the critical design.
Acquisitions:	The ordering and receiving of parts necessary to fabricate the satellite transceiver.
Fabrication:	The fabrication of the satellite transceiver.
Integration:	Integrate the satellite transceiver with the onboard satellite computer and the ground transceiver.
Testing:	Ensure a robust design and proper functionality.

6.5.2 Ground Transceiver:

Critical design:	Detailed design of a transceiver on the ground that will effectively transfer and receive data at the ground at a specified rate.
Funding:	Funding for the parts specified in the critical design.
Acquisitions:	The ordering and receiving of parts necessary to fabricate the ground transceiver.
Fabrication:	The fabrication of the ground transceiver.
Integration:	Integrate the ground transceiver with the satellite transceiver and the terminal node controller.
Testing:	Ensure a robust design and proper functionality.

6.5.3 Terminal Node Controller:

Critical Specification:	Detailed specification of a terminal node controller that will effectively modulate and demodulate the signal to and from the ground station.
Funding:	Funding for the parts specified in the critical specification.
Acquisitions:	The ordering and receiving of parts necessary to fabricate the
Integration:	Integrate the terminal node controller with the ground transceiver and the control computer.
Testing:	Ensure a robust design and proper functionality.

6.5.4 Control Computer:

Critical Specification:	Detailed specification of a control computer that will effectively route data and interface between the terminal node controller and the WWW server.
Funding:	Funding for the parts specified in the critical specification.
Acquisitions:	The ordering and receiving of necessary parts.
Integration:	Integrate the control computer with the terminal node controller and the WWW server as well as the tape drive and alphanumeric paging system.
Testing:	Ensure a robust design and proper functionality.

6.5.5 Server:

Critical Specification:	Detailed specification of a WWW server which will archive scientific data and present it on the WWW.
Funding:	Funding for the parts specified in the critical specification.
Acquisitions:	The ordering and receiving of necessary parts.
Integration:	Integrate the server with the control computer and the Internet.
Testing:	Ensure a robust design and proper functionality.

6.6 Available and Missing Resources

One of the most attractive aspects of this project being a University project is that we have the potential of having the full weight of the University behind us. For the purposes of the Tracking, Telemetry and Control subsystem, there are several groups that can be of great assistance to us.

The U of A's ECE department has a lot of equipment available for use by students, including the U of A's only spectrum analyzer that goes up into the EHF range. The ECE department can contribute a lot of resources both in the development and testing phases. We can also look into having a senior project design team take on our project.

The Lunar and Planetary Lab's Electrical Engineering lab is available to us to construct circuitry on a pay-per job basis.

The U of A's amateur radio club can help us in implementing our communication protocol and in investigating microwave communications. They are slated for a microwave antenna installation by the end of summer, 1997. By then they will have equipment that works at 1.2 GHz and 2.4 GHz and downward. Working with them as partners on Amateur frequencies would also make ARRL grant money available.

An AMSAT alliance would provide expert guidance and availability of otherwise inaccessible resources. These might include circuit design and construction, frequency use, and technical assistance.

Since the U of A maintains its own T1 Ethernet domain, as long as the Groundstation is located on campus, it is possible to get hooked up to the Internet for free. It is also possible to use interdepartmental requisitioning to obtain many computer and electronic parts and equipment.

We are also looking into getting industrial partnership with some local companies, including Motorola and Hughes, who might be interested in assisting the development of this high data-transfer rate subsystem.

6.7 Estimated Budget

The cost of the subsystems will depend on which frequency range is chosen. However, a general idea of the cost of components for both the ground station and the spacecraft is shown in Table 6.5.

Table 6.5 TTC Estimated cost of subsystem components

Component	Cost ($)
Antennas	1000 – 2000
EHF Wide-Band Transceiver	3000 – 6000
Amplifiers (LNA's, etc.)	1000 – 4000
Filters	1000 – 2000
Mixers	200 – 500
Crystal Oscillators	1000 – 2000

Control circuitry (phase lock loop, detectors, etc.)	1000 – 3000
Cable	1000 – 3000
Other (circulators, attenuators, misc.)	500 – 5000
Command Computer & Software	2000 – 5000
Database Server & Software	3000 – 10000
Terminal Node Controller	1000 – 3000
Ethernet Connection (2 years)	0 – 20000
Ethernet hub	200
Antenna positioning equipment	2000 – 4000
Modem & paging system	2000 – 3000
Misc.	1000 – 5000
Total	20900 – 77000

Table 6.6 Estimated cost of mentor work hours	
Component	Monthly Estimated Cost ($)
Steve Bell (est. $30/hr, 7.5 hrs/wk)	900/month
Matthew Cheselka (est. $15/hr, 7.5 hrs/wk)	450/month
Total	15500

Table 6.7 Estimated cost of student work hours	
Component	Cost ($)
10 – 15 Students (est. $7/hr, 12 hrs/wk)	3360 - 5040

Table 6.8 Overall estimated budget	
Grand Total	$39,760 - $97,540

7. Science and Technology Initiative, Laser Communication System

7.1 OBJECTIVES

The primary objective of this task is to design and construct a reliable and efficient laser communication system for the University of Arizona's Student Satellite. The main step toward achieving this goal is to develop a ground station and laser uplink to communicate with the low earth orbiting UASSP satellite, with the overall aim of providing data transfer at a higher data rate (>10 Mbps) than standard radio and microwave communications. An important secondary objective is to create a laser downlink from the UASSP satellite to the ground station. Accomplishing this objective entails using a light weight, low powered laser onboard the satellite, coupled to the planned onboard telescope.

The communication links will use lasers operating with wavelengths in clear atmospheric transmission windows. Currently under consideration are a Neodymium Yttrium Aluminum Garnet laser (Nd:YAG, CW, 1.064 micrometers) and an Indium Gallium Arsenic Phosphate semiconductor diode laser (InGaAsP, CW, 1.55 micrometers).

Central to this task is the establishment of an optical Groundstation. This ground station will require the use of a telescope with a tracking rate capable of following the satellite through its orbit over Tucson. If possible, a local observatory will be utilized with a minimal amount of modification. If necessary, a separate dedicated scope will be procured and adapted. It will be necessary to provide a fast link between the optical Groundstation and the main satellite ground control station. One possibility for this link would be to use a land based, lasercom system between the two stations.

7.2 APPROACH

Implementations of optical communication systems between a Groundstation and a satellite in orbit are fairly new. To this date there are several such systems that are still in the experimental phase. One such system was the Ground - to - Orbit Lasercom Demonstration (GOLD) conducted by the Jet Propulsion Laboratory [1]. In this experiment a laser communication link was repeatedly established between the Japanese Engineering Test Satellite (ETS - VI) and a ground station at JPL's Table Mountain Facility in Wrightwood, California. This project demonstrated the successful transfer of data at a rate of over 1 Mbps. The uplink in this experiment utilized a 0.6 meter telescope and an Argon Ion laser operating at a wavelength of 514.5 nm. The lasercom downlink used a semiconductor diode laser operating at 830 nm and a 1.2 meter receiving telescope.

A second such experimental project is being organized by the AstroTerra Corporation and Jet Propulsion Laboratory [2]. This system is scheduled to be launched in 1998 on the Space Technology Research Vehicle (STRV - 2). Using semiconductor diode lasers, this lasercom system is expected to transfer data at a rate of 1.2 Gbps between the Groundstation and a low earth orbiting satellite.

These experimental projects demonstrate the feasibility of using a lasercom system to communicate with the UASSP satellite. In order to achieve this goal, extensive research and study is involved. Through the work of the students, mentors, and others assisting with the Student Satellite Project, a model for the project will be designed. With further experimentation, design refinements, and modifications over the course of this project, it is hoped that the UASSP satellite will be launched with a lasercom system onboard.

[1] Wilson, K.E. "TDA Progress Report 42-124: An Overview on the GOLD Experiment Between the ETS - VI Satellite and the Table Mountain Facility." Jet Propulsion Laboratory, Communication Systems and Research Section. Feb. 15, 1996.

[2] AstroTerra Corperation Information . Copyright 1996 by AstroTerra Corporation. Internet, http://www.astroterra.com/company.html. Accessed: June 12, 1997.

7.3 INSTRUMENT DESCRIPTION

The following component choices are based on the results of the preliminary requirements analysis operating in the near infrared rather than the visible, improves atmospheric propagation quality, reducing index of refraction fluctuations and overall particulate scattering.

- Ground laser - a laser is needed at the ground station to send data up to the satellite. The two types that we are considering are: 1) A GaAlAs semiconductor laser with a wavelength of 1500 nm. This laser will have a peak power of 50 mW or less. 2) A Nd:YAG/YLF/YAP solid state laser with a wavelength of 1064 nm. This laser will have a peak power of 1 - 5W. Both of these lasers were chosen, based on their wavelength, because of their ability to easily propagate through the atmosphere. In addition to this, commercial fiber optic / laser manufacturers are moving to 1 micron or larger wavelengths, increasing the number of available products.

- Satellite laser - a laser is needed onboard the satellite to send data down to the groundstation. The GaAlAs semiconductor laser with a wavelength of .8 - 1.6 μm. This laser will have a peak power of 50 mW or less. This type of laser was chosen for its low power requirements, ease of mounting, and minimal space and weight requirements.

- Narrow bandpass filter - This component will be able to filter out unwanted noise out of the detector. Photo detectors - Tentatively both the ground station and the satellite will be using one of the following photo conductive detectors, selection being made based on the final requirements analysis.
    - PbS Lead Sulfide
    - PbSe Lead Selenide
    - PbTe Lead Telluride
    - InSb Indium Antimonide
    - Si doped Silicon
    - Si PIN Silicon
    - Avalanche

- Heterodyne mixer - Mixes the electric field of an incoming beam with the electric field of a local laser oscillator, using an optical beam combiner, to produce a strong received signal. To be used in the ground station receiver, and in one onboard receiver if indicated by final requirements analysis.

- Amplifier - A high gain, low noise, low power amplifier is needed. For example, a low noise JFET input OP amp could be used depending on the amount of power received by the detector.

- Data Processing - Consists of two separate processing stages operating in ATM or similar digital data transmission mode. The first stage is the forward error correction processing unit (FEC), which will operate at the byte cell level. The second stage is the cyclic redundancy check processing unit (CRC), which will operate at the multi-cell packet level. If possible, the FEC will directly correct cells containing flipped or missing bits using redundant information contained within one cell. If the cell cannot be corrected, or if part of the packet is missing, the CRC will detect this and will request re-transmission via the satellite's downlink. The CRC will also execute higher-level data handling, such as reordering transmitted information. In this way, it is hoped to reduce overall link error rates to levels comparable to terrestrial digital communication links (10^{-12} - 10^{-15} error bit / valid received bit).

Overall Instrument Block / Data Flow Diagram

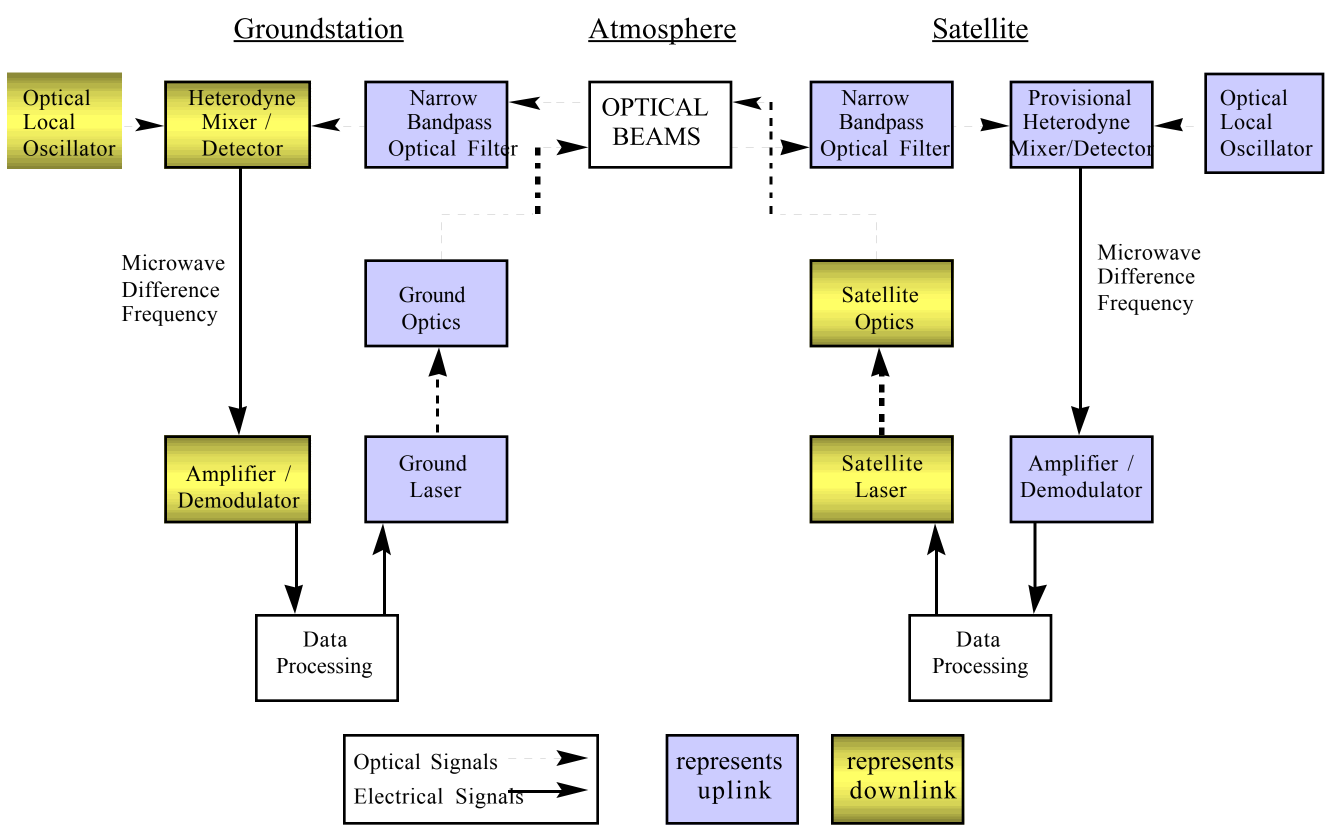


Figure 7.1 Overall Instrument Block/Data Flow Diagram

7.4 RESOURCES

7.4.1 Available

- University of Arizona - Physics Department and other departmental shared computer facilities.

- Saratov State University, Russia - (possible) cooperative project to develop land based, laser communication system

7.4.2 Needed

- Laboratory (equipped) with optical and data communications test equipment. Specifications to be announced.

- Transmitter - Different laser transmitters for testing and research. These include the GaAlAs semiconductor type and Nd:YAG/YLF/YAP solid state types. Others may be necessary, once further research / design has been done.

- Receiver - a sufficient spectrum of photo detectors for testing and research, most likely to be Si PIN or Avalanche phoconductive detectors.

- Computers - approximately two high speed notebooks and two desktop computers (Pentium or later generation) with 10/100 Mbps Ethernet capabilities.

- Software - software needed for design, testing, and research will include Mathematica, PSPICE, C/C++ compilers, ray tracing / diffraction software, AutoCAD, an Office Suite, satellite tracking software (if not facilitated), field testing software.

- Optical groundstation - Which will include a telescope, optical equipment, a high speed tracking mount, a high speed Internet/intranet connection with a computer. Existing facilities will be researched, and if none meet our requirements, one will have to be built.

- Tools - The majority of the tools needed, such as breadboards, circuit components, etc., will be purchased when there is a greater understanding of the circuitry involved.

- Machine and optical shop time for fabrication of precision electromechanical and optical components.

7.5 DIVISION OF LABOR:

Below is a table of personnel estimates accompanied by a table of current personnel. Although we have outlined that individuals will be performing specific tasks, given his/her specialty, each person will participate in the actual construction and implementation of the final project. For example, the person(s) in charge of constructing the optics components of the communications system will also be involved with developing other aspects such as modulation schemes and electronic filter design. At present the STI Subteam is only responsible for the development of the a laser communications system. This, however, is not its limit of the STI Subteam’s responsibility. If other projects become associated with the STI Subteam the personnel required will change. Therefore, this list is only a preliminary estimate of resources required and is subject to change.

In the table below any occurrence of faculty mentor can be replaced by an industry expert

Table 7.1 STI Division of Labor	
STI Subteam	Personnel Needed (Estimated)
Laser Implementation Subteam	• 3 Electrical/Computer Engineers (one faculty and two students for data handling and processing) • 2 Physicists (one faculty mentor and one student for laser modeling) • 2 Computer Scientists[1] (one faculty and one student for software integration with laser and tracking mount control) • 2 Optical Engineers (one faculty and one student for optical design)
	Current Personnel
	• 4 Electrical/Computer Engineers who are Joseph Gordon, Mitesh Patel, Matt Gilbert, and Chris Gee • 1 Physicist who is Dr. William Wing • 1 Optical Engineer who is Paul McMurtry

(1) Computer Scientists should be familiar with error correction and network protocols.

7.6 SCHEDULE

At this point in the project, several milestones have been established. Over the summer of 1997, which will be one of the must crucial time periods of the project, the preliminary design of the laser communication system will be completed. For feasibility testing, the following type of test plan may be considered: There will be incremental testing phases which will test the limits of current designs for the laser communication system. Basically, each phase will test distances differing by a factor of 10. So, the first test phase will be 10-100 meters; the second, 100-1000 meters; and so on. We plan on having between 4-5 test phases, depending on the resources available to test the larger distances.

Table 7.2 STI Schedule		
Task / Activity	Start Date	End Date
External Proposal Writing	05/19/97	06/13/97
Draft of requirements for TT&C		6/10/97
Draft of requirements for Science Team		6/11/97
"Fact List" for Project Level Proposal		6/13/97
Submission of External Proposal	06/20/97	
Preliminary Design	06/16/97	10/03/97
Rough feeling for design, sound		
calculations, acquire and	06/20/97	07/01/97
understand equipment		
Develop Test procedures, prove	07/21/97	08/25/97
feasibility, start testing phase		

Know how pieces work	09/01/97	10/01/97
Start preliminary design work		
Preliminary Design Finished		10/1/97
Proposal revised appropriately		
Preliminary Design Review	10/06/97	10/08/97
Detailed Design	10/09/97	12/05/97
Critical Design Review	12/08/97	12/10/97
Long-lead procurement	10/09/97	
Fabrication	01/05/98	08/28/98
Testing and Calibration	05/18/98	07/18/98
Integration (including prep)	08/31/98	02/26/99
Final testing and Calibration	02/28/98	05/26/99
Ready for Delivery	06/05/99	
Request for Launch	TBA	
Launch	TBA	

7.7 ESTIMATED BUDGET

For the first part of the budget , the time costs incurred to this point of the project, along with projected time will be considered. The second part of the budget will be broken up into two sections: one for the equipment and materials needed to design, build, test, and calibrate the equipment, before the final integration stage; the other for possible facility costs. The following cost estimates include direct costs only.

Table 7.3 Estimated time for team members and mentor(s)		
	Time Spent (up to 6/22/97)	Projected Time (for next 2 years)
Per Team Member (5 team members presently)	15 hours * 5 team members = 75 Hours	20,000 hours (including 5 new team members)
Current Mentor (Dr. Wing)	100 hours	1,000 hours
4 Additional mentors (hopefully from ECE / PHYS / OPTSCI / CS	0 hours	1000 - 4,000 hours
Total estimated time	175 hours	22,000 - 25,000 (over 2 years)

Equipment Costs (based on the block diagram, assuming a downlink and uplink)
key: * = uplink
** = downlink
*** = uplink and downlink

Table 7.4 Equipment Costs (based on the block diagram, assuming a downlink and uplink)		
	Item	Cost

Groundstation	Computer, ATM interface hardware, storage	$5,000.00
	Amplifier / Demodulator **	$500.00
	Local Oscillator Laser	$1,000.00
	Laser (semiconductor) *	$3,000.00
	Ground Optics (includes telescope, laser optics) *	refer to facility costs
	Heterodyne Mixer ** / Detector (Si PIN photodiode or APD, plus electronics) **	$6,000.00
Test Equipment	Narrow Band Pass Optical Filter ***	$2,000.00
Satellite	Laser calibration, optical breadboards / lens kits, possible test lasers from Saratov State University	$30,000.00 (hopefully a majority of test equipment like oscilloscopes, hardware development systems, software prototyping can be done with U of A equipment)
	On-board processing / storage with a dedicated processor / DSP, connected to the main spacecraft computer	$5,000.00
	Local Oscillator Laser	$1,000.00
	Laser (solid state) **	$3,000.00
	Amplifier / Demodulator *	$2,000.00
	Satellite Optics **	Science team will design the majority of the equipment, costs will be factored in by them
	Heterodyne Mixer (including an additional laser) / Detector (Si PIN photodiode or APD, plus electronics) *	$6,000.00
	Narrow Band Pass Optical Filter + mirror ***	$2,000.00
Total Cost for equipment		$66,500.00

Table 7.5 Possible Facility Costs	
Scheduling of time on a local area telescope (Kitt Peak or Mt. Lemmon or private) for the optical groundstation	$10,000.00 (if a facility can be found) $20,000.00 (if a facility can not be found)
Use of environmental testing facility (thermal, vacuum, vibration, radiation testing)	$8,000.00
Leasing of lab space for construction / testing	use U of A facilities (read this as possibly free)
Total Cost for Facilities	$18,000.00 - $28,000.00

Estimated Grand Total (including 10% for shipping, sales tax)	$92,750.00 - $103,750.00

8. Team Composition

8.1 Science Team

8.2 MSA Team

Team Leader: John Scharf

Team Members

Sam Brean
Chris Greene
Scott Golper
Matt Johnson
Chak Leung
Stephanie Loutzenhiser
Bill Oswald
John Rascon

Team Mentor

Dr. Weinong “Wayne” Chen

8.3 GNC Team

8.4 PGD Team:

Leader – David Lundell
Flywheel Sub team Leader – Matthew Rippa
Distribution Team Leader – Brian Hack
Members: Adolpho Caballero, Greg Chatel, Creighton Anderson, Sheena Baccus, Tony Yousenfejad

8.5 DCH Team

Todd Brandt
Ken Huizenga
Rex Newbould (Leader)
James Tankersly

8.6 TTC Team

Name	Area
Michael Craig	*Team Leader*
Harold Russell	*Deputy Leader*
Chris Koehler	*Groundstation Team*
Dana Irvin	*Telemetry Team*
Scott Raby	*Telemetry Team*

Erik Herman	***Telemetry Team***
Matthew Cheselka	
Steve Bell	9. Team Mentor ***Telemetry Mentor***

8.7 STI Team

Team Leader
Christopher Gee

Team Members
Joseph Gordon
Mitesh Patel
Matt Gilbert
Paul McMurtry

Team Mentor
William H. Wing

9. Table of Figures