A SATELLITE-BASED IMAGING SYSTEM FOR ATTITUDE DETERMINATION AND REMOTE SENSING

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ABSTRACT

This paper describes a six year effort to conceptualize, design, and build a space-based imaging system called SEASIS. SEASIS includes panoramic and telephoto imaging subsystems and will be housed in a satellite to be deployed from the Shuttle via a tethered system in June, 1997.

During deployment, tether dynamics will be studied from the satellite's perspective by combining panoramic images acquired by SEASIS with data recorded by onboard accelerometers. This approach will allow the oscillations of the satellite to be decoupled from the forces imposed on it by the tether. After deployment is complete, and the tether has been severed, the satellite will serve as a remote sensing platform. The telephoto and panoramic images of the Earth, captured by SEASIS, will be used to expedite optical studies of the atmosphere.

1. INTRODUCTION

The National Aeronautics and Space Administration (NASA) Headquarters has approved a microsatellite, being built by members of the Students for the Exploration and Development of Space (SEDS), called SEDSAT. Plans call for SEDSAT to be deployed using a tether via NASA's Small Expendable Deployer System on shuttle mission STS 85 in June 1997. The objective of the SEDSAT mission during deployment is to study the dynamics of the tether from the perspective of the satellite. This will be accomplished by combining images, acquired using an onboard imaging system called SEASIS, with data taken from a three-axis accelerometer system. Once deployed, SEDSAT will serve as a remote sensing platform.

SEASIS (The **S**EDS **E**arth, **A**tmosphere, and **S**pace **I**maging **S**ystem) is a low cost, flexible system designed to capture and record sufficient imagery during deployment so that the attitude of SEDSAT can be determined in ground based post processing [1]. The synthesis of this information with accelerometer data will allow the forces acting on the satellite to be determined. Once the tether has been severed, SEASIS is designed to acquire images of the Earth for optical studies of atmospheric absorption bands in the visible spectrum.

This paper describes how the data from SEASIS will be used to verify and/or improve analytical models for tether dynamics. The paper begins by introducing the reader to the basic equations of tether technology. A number of potential applications for tethered systems are presented; the role to be played by SEASIS during tether deployment is clearly defined. Then, an overview of the SEASIS system design is described. This discussion is followed by a summary of typical space flight attitude determination systems and how SEASIS incorporates a unique Panoramic Annular Lens (PAL) to provide a novel solution for attitude determination.

2. TETHER TECHNOLOGY

2.1. Background

For nearly a century, concepts involving tethers have been documented worldwide and, in the last twenty to thirty years, studies of tether dynamics and control laws have been ongoing to aid in understanding tether dynamics in space. A tethered system, in the context of space flight, may be defined as two masses connected by a tether (string, cord, cable, etc.). Most simulations are based on Newtonian dynamics and involve two masses, traveling in different orbits, constrained by a tether.

Space-based tethered systems are gaining increasing acceptance because they offer significant cost savings over conventional propulsion systems for boosting and returning payloads from Low Earth Orbit. There is substantial literature arguing that operations involving the transfer of orbital energy and payloads via tethers will become common in the 21st century [2]. However only a handful of tether experiments have been conducted and, while more ground-based work could be performed, additional flight tests are required to demonstrate and verify the analytical models and control schemes related to tether technology.

The first flight test of a tethered system in space occurred in November, 1966, when a 200 m long tether was used to join Gemini 11 and 12. Subsequent experiments were conducted between Gemini 12 and the Atlas/Agena D spent stage. Additional tether experiments were conducted by the Japanese in the 1970's using sounding rockets. The joint Italian/U.S. Tethered Satellite System, TSS1, which flew in June, 1992, initiated advanced operational studies of tethers. The NASA Small Expendable Deployer System (SEDS), flown in 1993 and 1994, began a series of low cost missions to further tether dynamics studies. Other efforts in orbital tether research include the Commonwealth of Independent States MAK-T small satellite deployer system; it is not clear, however, whether or not this system has actually flown [3].

2.2 Tether Dynamics

The dynamics of a two body tethered system orbiting the Earth is, to a first approximation, relatively simple. In general, the tethered system takes advantage of the fact that two bodies orbiting around the Earth at different altitudes travel at different velocities. Figure 1 shows the forces acting on a satellite of mass m orbiting the Earth in a circular orbit of radius, r, with velocity, v. The angular velocity, ω, and the orbital period, T, are given by,

$$\omega=\frac{v}{r} \quad (1) \qquad \text{and} \qquad T=\frac{2\pi}{\omega} \quad (2)$$

respectively.
The centrifugal force is given by

$$F_c = mr\omega^2 \quad (3)$$

while the gravitational force is obtained from Newton's law of gravitation as,

$$F_g = \frac{GMm}{r^2} \quad (4)$$

where G is the universal gravitational constant (6.673 x 10^{-11} Nm^2/kg^2) and M is the mass of the Earth (5.979 x 10^{24} kg). These forces must be equal and balanced at the center of gravity. Equating the gravitational and centrifugal forces,

$$\frac{GMm}{r^2} = mr\omega^2 \quad (5) \qquad \text{and} \qquad \omega^2 = \frac{GM}{r^3}. \quad (6)$$

Applying Equation 1,

$$v = \sqrt{\frac{GM}{r}} \quad (7) \qquad \text{and} \qquad T = \sqrt{\frac{4\pi^2 r^3}{GM}}. \quad (8)$$

Figure 2 shows the forces acting on two masses when they are tethered in a simple "dumbbell" configuration. When the tether is oriented such that there is a vertical separation between the two masses, the upper mass experiences a larger centrifugal force than gravitational force, and the lower mass experiences a larger gravitational than centrifugal force. The result is a force couple system which constrains the tethered system to remain in a vertical orientation. Displacing the system from the local vertical produces restoring forces which act to return the system to its original configuration.

If the two masses were in different orbits and were not connected by a tether, their orbital speeds would be given by

$$v_1 = \sqrt{\frac{GM}{r_o + L}} \quad (9) \qquad \text{and} \qquad v_2 = \sqrt{\frac{GM}{r_o - L}} \quad (10)$$

respectively, where r_o is the altitude of the center of gravity and L is the tether length measured from the center of gravity to one of the masses (i.e., the tether is assumed to be of length 2L). Equations 9 and 10, show that, without the tether, the upper mass would move at a slower speed and the lower mass would move at a higher speed.

Assuming that the center of gravity of the tethered system coincides with its center of mass and that the two masses are equal, the velocity of the system can be found by equating the gravitational and centrifugal forces at its center of gravity. Assuming the mass of the tether to be negligible,

$$\frac{Gm_oM}{r_o^2} = m_o r_o \omega_o^2 \quad (11)$$

where m_o is the total mass of the tethered system and ω_o is the orbital angular velocity of the center of gravity. Solving Equation 11, for ω_o,

$$\omega_o = \sqrt{\frac{GM}{r_o^3}} \qquad (12)$$

The corresponding orbital velocity, v_o, is given by,

$$v_o = \sqrt{\frac{GM}{r_o}} \qquad (13)$$

whereas, the orbital period, T_o, is

$$T_o = \sqrt{\frac{4\pi^2 r_o^3}{GM}} \qquad (14)$$

Equations 12, through 14, show that the angular velocity, orbital velocity and period depend on the orbital radius, and are independent of the tether system mass.

Comparing Equation 13, with Equations 9 and 10, it is observed that the tether speeds up the upper mass and slows down the lower mass. The resulting upward acceleration of the upper mass and downward acceleration of the lower mass give rise to a tension in the tether. They also produce restoring forces when the tether is deflected from the vertical configuration. A gravity-gradient force results on each mass which is equal to the difference between the centrifugal and gravitational forces acting on the mass. An approximate value for this force is [2]

$$F_{gg} = 3Lm\omega_o^2. \qquad (15)$$

These gravity-gradient forces play a critical role in tether dynamics and form the basis for the potential practical tether applications discussed in Section 2.3.

In reality, the analysis of a tethered system is much more complex. For example, the gravitational acceleration changes nonlinearly with the distance to the center of the Earth; consequently, the center of gravity of the tethered system does not coincide exactly with its center of mass. This separation between the center of mass and the center of gravity becomes more pronounced as the tether length increases. The analysis becomes far more complex when the masses are unequal and when the mass of the tether is considered, not to mention the additional forces generated during deployment. Even when a tethered system is in a vertical configuration and theoretically stable, there are forces which may cause it to vibrate (oscillate) about the vertical. These weak but persistent forces include atmospheric drag and, for conducting tethers, electrodynamic forces. This makes the analysis of the gravity-gradient difficult, and the accurate analysis of a tethered constellation (a generic distribution of more than two masses in space connected by tethers) extremely complex.

The difficulties encountered in accurately analyzing even the most simple tethered system was a major motivating factor in developing SEDSAT. The data gathered by its unique combination of electronics and optics will allow complex computer models associated with tether dynamics to be verified or adjusted. This knowledge will make it possible to exploit the tether applications discussed below.

2.3 Tether Applications

As the human race moves into space, the construction and use of relatively large tethered platforms will be important to lowering the cost of space transportation. Figure 3 shows a configuration which utilizes Shuttle external tanks in a raft format to form a structure in space. In this example, tethers are used as structural elements in an evolving space station and for links (power, data transfer, etc.) between different platforms designed for various science and materials processing applications. Some of the platforms would share resources, while being individually isolated from contamination and mechanical disturbances. Others could be used to facilitate storage of liquid propellants and other dangerous fluids, or to provide variable/controlled environments to study the long-term effects of lowered gravity levels on humans [4,5].

In addition to linking structures, tethers can be used to control the center of gravity of structures. Figure 4 shows two tethers with end masses deployed vertically (one above and one below) from the Space Station. The tethers are attached to a laboratory facility, located at the vertical center of gravity of the Space Station, which would be used to conduct microgravity experiments (10^{-4} g and less) for extended periods of time. The microgravity environment would be maintained by varying the lengths of the tethers to control the Space Station's center of gravity [2].

Tethered systems for transportation have been widely publicized. Most applications capitalize on their ability to transfer momentum between two bodies. Figure 5, for example, illustrates the use of a tether initiated space recovery system that provides a means of transferring a small payload (such as processed chemicals, archived engineering and experiment data, etc.) from the Space Station to the Earth without the use of the Shuttle Orbiter or a fueled retropropulsion system. The tethered payload would be released into a reentry trajectory such that it would enter the upper atmosphere within one-half orbit. During reentry, a parachute would open, slowing it to permit a soft landing [6].

Tethers also offer a unique opportunity for planetary remote sensing. Figure 6 shows a satellite in a stable lunar orbit with analysis instruments tethered downward. Since the tether can be lowered as close to the lunar surface as desired, sensitive measurements can be made at altitudes unsuitable for lunar satellites. The proposed scenario shows the satellite in a 300 km stable orbit with the tethered payload 50 km above the lunar surface. Sensitive measurements of the lunar environment and surface can be taken as part of site selection and preparation for lunar outposts [7].

Tethers may have a large impact on Space Station waste disposal. Currently, the only source for removal of waste would be the shuttle Orbiter, once every 90 days. This poses a potential health hazard for Space Station occupants. Figure 7, however, shows a tethered trash disposal scenario in which tethers are employed to deorbit waste into the Earth's upper atmosphere where it would completely disintegrate. Trash disposal could be achieved easily, at the leisure of the Space Station occupants.

All of these applications require a system for tether deployment. NASA's Small Expendable Deployer System can be used, in a cost effective manner, to validate the great potential of tether applications in space. This system will be used to deploy SEDSAT, and it is discussed in detail in the following section.

2.4 The Small Expendable Deployer System (SEDS)

NASA has built two tethered systems for near term flight demonstrations and orbital operations. The first is the Tethered Satellite System (TSS), a three hundred and seventy nine million dollar investment built by the Italian Space Agency, which flew with limited success on Shuttle flight STS 46. TSS is scheduled to fly again in February, 1996. The Small Expendable Deployer System (SEDS), on the other hand, is a lightweight spinning-reel system designed to deploy a payload attached to a non-recoverable tether with a length of up to 40 km.

The tether is made from a high-strength, low-density polyethylene fiber called SPECTRA; when taut the tether is less that 1.0 mm in diameter [8]. This material has recently become commercially available in the form of multistrand fishing line. To date, SEDS has flown two missions, both of which were completely successful [9]. SEDSAT is scheduled for deployment via a 20 km tether on the third SEDS mission.

2.5 SEASIS and Tether Deployment

As a result of the first two SEDS missions, and first flight attempt of TSS, the behavior and dynamics of tether deployment are now better understood. In the TSS mission, however, the behavior of the end mass influenced the success of the deployment and underscored the importance of understanding the complex relationship between the end mass and the tether. SEASIS will, for the first time, provide a visual record of deployment from the end mass perspective. The time stamping of image data relative to the acceleration data gathered by a three-axis accelerometer system (TAS) will allow researchers to gain a better understanding of the forces imparted to the end mass during tether deployment [10]. This knowledge will drive the designs of future deployers which may incorporate different winding patterns and deployment control laws. The result will be to increase the confidence of the space user community in this new, and cost effective technology.

3. SEASIS

3.1 System Design

During SEDSAT deployment by the SEDS, SEASIS will capture and store images for later downlink to earth. These images will be processed to determine SEDSAT's attitude during the deployment sequence. This data, in conjunction with that taken by TAS, will provide vital insights into the dynamics of the tether deployment from the perspective of the end mass (SEDSAT).

After SEDSAT has been deployed, and the tether has been cut, the post deployment phase of the SEDSAT mission will begin. SEASIS will serve as a remote sensing platform, capturing images in the ten different bands spanning the visible and near IR regions. These images will be used to study the optical properties of the atmosphere for calibration and validation of an atmospheric corrections algorithm. SEASIS images will also be used to study surface energy budgets, cloud cover types and movement, lightning types and frequency, and other Earth resources.

Due to the very different objectives of SEASIS during deployment and post deployment, the optical design was divided into two subsystems [11]. As shown in Figure 8, the panoramic imaging subsystem and the telephoto imaging subsystem share processing and control electronics, and have duplicate filter wheels, encoders and cameras; the only difference between the two subsystems is the lens assemblies.

The telephoto system has a telephoto lens with a 10 degree field of view (FOV) that will be pointed nadir (toward the Earth) after SEDSAT has reached its final orbit. The PAL system has a panoramic annular lens which will be pointed 90 degrees away from nadir. Both systems have a filter wheel which has 6 narrow band filters, 4 broad band filters, and 2 neutral density filters. They also have a Sony CCD camera that will capture the images focused onto the image plane by the lenses. SEASIS has one video digitizer that will digitize images from the cameras. A Space Computer Corporation 100 (SCC-100) multichip module is the processing unit for the imaging system. Images will be stored in 1 Gigabit of onboard static memory, also a part of SEASIS.

As described later in this paper, the panoramic system utilizes a unique panoramic annular lens (PAL) which makes it possible to completely determine the attitude of SEDSAT with a single sensor. The telephoto system, on the other hand, is designed with a 10° FOV lens and a filter wheel so that observations of the Earth and atmosphere can be made in ten discrete bands. The filters were chosen to isolate atmospheric absorption bands critical to the determination of the optical properties of the atmosphere.

3.2 Attitude Sensors

A number of conventional attitude sensors were considered for the task of SEDSAT attitude determination including sun sensors, Earth horizon sensors, star sensors, and magnetometers. Sun sensors are visible-light detectors that measure one or two angles between the sun's incident radiation and the detector [12]. They typically have an accuracy between 0.01 - 3.0 degrees and can even be as accurate as 0.005 degrees; however, they require clear fields of view and only provide one of the two external vectors required for 3-axis attitude determination [13]. For this reason, sun sensors are commonly used in concert with horizon sensors to determine the 3-axis attitude. Though magnetometers are often not as accurate as sun sensors (0.5 - 3.0), in some cases, they are added to the sensor suite to assure attitude determination when the sun is eclipsed.

Horizon sensors, on the hand, operate in either the visible spectrum or the infrared with accuracies from 0.03 - 1.0 degrees [12]. Most horizon sensors scan across the Earth in a very narrow FOV, and record the time between crossings of the Earth limb. This information is used to determine the Earth's angular radius which provides one of the two external vectors required for determination. Visible horizon sensors utilize the Earth's albedo (day side), and the Earth's air glow (night side) as limb reference points. Infrared sensors detect the Earth's infrared radiation, typically in the 15 μm carbon dioxide band (CO_2), and are the most common type of horizon sensor used today. Infrared horizon sensors can have accuracies as high as 0.03 degrees with typical values ranging 0.1 - 0.25 degrees. The added accuracy of an infrared sensor comes with the addition of cost, weight, and complexity [14]. Most require additional components such as heat sinks and germanium immersion lenses [15]. They also must be coupled with at least one other sensor to provide an additional external reference vector.

Star sensors are the most accurate type of attitude sensor (0.003 - 0.01 degrees), and can be categorized into two groups: star trackers or star mappers [13]. Star trackers search for specific stars within a wide FOV, while mappers record numerous stars and measure their angular separation. Comparison of the recorded information with a star catalog yields the orientation of the spacecraft. While star sensors can provide accurate three-axis attitude information, they are generally heavier and more power hungry than other attitude sensors, and are sensitive to stray light sources such as sunlight reflected from the spacecraft or the Earth, as well as sunlight scattered from dust particles and jet exhausts [13].

Magnetometers measure the strength of the Earth's magnetic field to determine attitude. They can be configured for one, two, or three-axis attitude determination with accuracies from 0.5 - 3.0 degrees. They are relatively simple, reliable, and lightweight when compared to other sensors; however, due to their lower accuracies, they are often combined with sun and horizon sensors [12].

During satellite deployment, oscillations of the tether will cause the satellite to tumble and oscillate in a pseudo "random" fashion. While the types of forces that will affect the tether, and thus the general behavior of the tether and satellite, are fairly well known, the exact effect on the movement of the satellite is not. Therefore, the attitude sensor(s) employed for SEDSAT must not require pointing. Moreover, due to the small size of SEDSAT, it is desirable to employ as few instruments as possible to accomplish a given task. If at all possible, the attitude sensor(s) should be able to perform multiple tasks.

In summary, sun sensors and horizon sensors must be used in combination with other sensors to achieve three-axis attitude determination, and have limited capabilities beyond attitude determination. Magnetometers can provide the three-axis attitude, but unless used in combination with other sensors, only achieve accuracies from 0.5 - 3.0 degrees. Again, they have limited capabilities beyond attitude determination. Star sensors would be the best choice due to their high accuracies (0.0003 - 0.01 degrees) and possible uses after the deployment sequence has ended. However, the random tumbles/oscillations of the satellite during tether deployment would make it extremely difficult to ensure that the sensor could be pointed toward the stars. These limitations led to the development of a panoramic imaging system for the determination of SEDSAT's attitude.

3.3 Panoramic Imaging System

As shown in Figure 9, the Panoramic Annular Lens (PAL) is a single element lens with spherical surfaces which works based on a combination of reflection and refraction [16]. The PAL forms an internal virtual image of its surroundings, a transfer lens is required to focus the virtual image onto the focal plane of an imaging device. As a result of the limited numerical aperture, the depth of focus of the PAL extends from the surface of the lens out to infinity; consequently, the lens assembly requires no focusing during operation.

The PAL's FOV extends from 20° below the horizon to 25° above the horizon, 360° around. Figure 10 shows a photograph taken at the Alabama Space and Rocket Center with a PAL camera pointed towards the sky.

The unusual FOV of the PAL provides a unique solution for SEDSAT attitude determination. It has been shown through analysis that the PAL sensor assembly can be used to acquire two external reference vectors for three-axis attitude determination with an angular resolution between 1.5 - 3.0 degrees, with no pointing required [14].

The PAL in combination with a transfer lens and CCD camera can be utilized as a combined sun and horizon sensor on the day side of the SEDSAT deployment orbit, and a combined star (or moon and planet) and horizon sensor on the night side of the orbit. The PAL will be mounted on SEDSAT parallel to the tether attach point. During the deployment sequence, the optical axis of the PAL will initially be pointed 90° with respect to the nadir vector. As illustrated by Figure 11, the Earth will appear within the FOV of the PAL. These wide arcs of the Earth limb will be used to determine the Earth's angular radius, ρ, as [13]

$$\rho=\sin^{-1}\left(\frac{r_E}{r_E+h}\right). \qquad (16)$$

The result from Equation 16 will be used to establish the nadir vector as an external reference vector. Figure 12 graphically describes the Earth's angular radius.

As the tether deployment continues, the PAL will be rotated through 90° so that it points directly nadir. Changes in the attitude of the PAL with respect to the Earth result in the wide arcs becoming more or less curved; they may even appear as a complete circle on the focal plane of the CCD camera when the PAL is pointed directly nadir or zenith as illustrated in Figures 13 and 14, respectively. For the SEDSAT deployment altitude of approximately 300 km, no matter what the orientation, the PAL will always have part of the Earth limb arc in its FOV.

The PAL will be able to determine a second reference vector by imaging the stars (and/or moon and planets) on the night side of the orbit, and the sun on the day side of the orbit. A 670 nm wavelength filter, 10 nm wide, will be positioned in front of the CCD camera during the day side of the orbit to decrease the chances of saturation by the sun. The 670 nm band is optimum for reducing the dynamic range between the intensity measured by the CCD of the direct irradiance of the sun, and the light transmitted from the sun through the Earth's atmosphere, reflected off the Earth's surface, and then transmitted back through the atmosphere up to the satellite. Also, the electronic shutter speed of the camera will be increased and the gain adjusted to compensate for the sun.

The primary function of the PAL imaging system is to capture imagery during the SEDSAT 90 minute tether deployment, but it will also will be utilized in scientific studies after the satellite is in orbit. To enhance the PAL's potential for further research, the filter wheel originally designed for the telephoto imaging system was duplicated for the PAL imaging system. The PAL is currently slated for studies which utilize its wide FOV, in the different spectral bands, for cloud cover, and lightning studies.

4. CONCLUSION

A space based imaging system, SEASIS, has been developed for incorporation into a satellite. SEASIS will collect data as the satellite is deployed, enabling researchers to verify and/or improve analytic models developed for tether dynamics. After deployment, SEASIS will be serve as a remote sensing platform for optical studies of the Earth's atmosphere.

The system is currently in final flight fabrication. After fabrication the system will be calibrated and characterized to determine resolution and performance. Extensive possibilities exist for software development; examples include software for real-time attitude determination during SEDSAT deployment, correlation routines for extracting information from the telephoto and PAL images, and automated procedures for atmospheric correction.

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6. REFERENCES

[1] Bankston, C. D., J. Gilbert, and D. Wingo, *Tethers and Their Role in the Space Exploration Initiative* , ASCE, Third International Conference on Engineering, Construction, and Operations in Space, May-June, 1992.

[2] National Aeronautics and Space Administration, *Tethers in Space Handbook, 2nd Edition,* Office of Space Flight Advanced Program Development, NASA Headquarters, Washington, D.C., 1989.

[3] Ordzhonikidze, S., *Research and Use of Tethered Space Systems Based on the MAK-T Small Artificial Earth Satellite,* Scientific-Research Institute of Applied Mechanics and Electrodynamics of the Moscow Aviation Institute, SSS-T Moscow, CIS 1991.

[4] Carroll, J. A., *Tethers and External Tanks, Chapter 3, Utilization of the External Tanks of the Space Transportation System, California Space Institute, La Jolla, CA, 1982.*

[5] Carroll, J. A., *Tethers and External Tanks; Enhancing the Capabilities of the Space Transportation System,* California Space Institute, La Jolla, CA, 1982.

[6] Final Report, *Tether Released Recovery*, NASA Contract NAS8-35096.

[7] NASA CP-2422, *Applications of Tethers in Space Vol. 1,* Workshop Proceedings, Venice, Italy, 1986, 127-151.

[8] Carroll, J.A., *Users Guide to SEDS, The Small Expendable Deployer System*, Energy Sciences Laboratory, Tether Applications, La Jolla, CA 1990.

[9] Carroll, J. A., *SEDS Deployer Design and Flight Performances,* AIAA 93-4764, Proceedings, AIAA Space Programs and Technologies Conference and Exhibit, Huntsville, AL 1993.

[10] Bankston, C. D., *SEASIS, Panoramic Imaging of Tethers in Space,* ASCE Southeastern Regional Student Conference, April, 1990.

[11] Bankston, C. D., *SEDS, earth, atmosphere, and space imaging system (SEASIS),* SPIE #2214-33, April 1994.

[12] Larson, W. J. and J. R., Wertz, *Space Mission Analysis and Design.* Microcosm Inc., Torrance, CA and Kluwer Academic Publishers, Dordrecht, The Netherlands, 1992.

[13] Wertz, J. R., *Spacecraft Attitude Determination and Control*. Reidel Publishing Company, Dordrecht, The Netherlands, 1980.

[14] Stedham, M. A., *Measurement of Spacecraft Attitude Via The Panoramic Annular Lens Attitude Determination System (PALADS),* M. S. Thesis, University of Alabama in Huntsville, 1994.

[15] National Weather Satellite Center, *Torques and Attitude Sensing in Earth Satellites,* Academic Press, New York, NY, 1964.

[16] Matthys, D. R., et al., *Endoscopic Inspection Using a Panoramic Annular Lens,* Proceedings, SPIE 1991 International Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, CA, July 21-26, 1991.

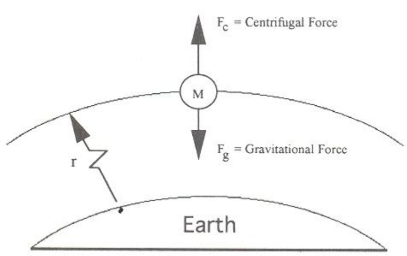

Figure 1. The Forces Acting on a Satellite of Mass m Orbiting the Earth

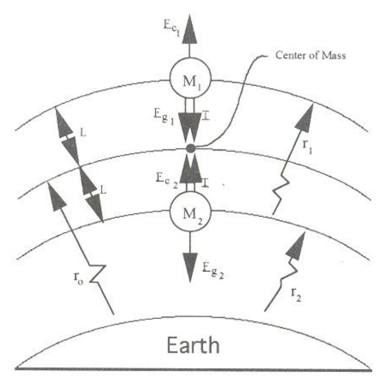

Figure 2. The Forces Acting on Two Masses When Tethered Together

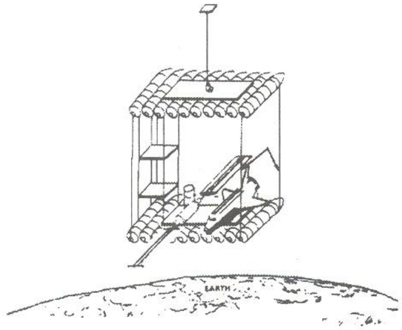

Figure 3. Tethers Used as Structural Elements for Large Structures in Space

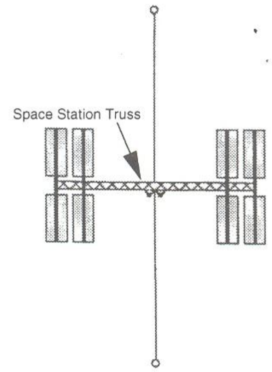

Figure 4. Microgravity Experimentation Utilizing Tethers

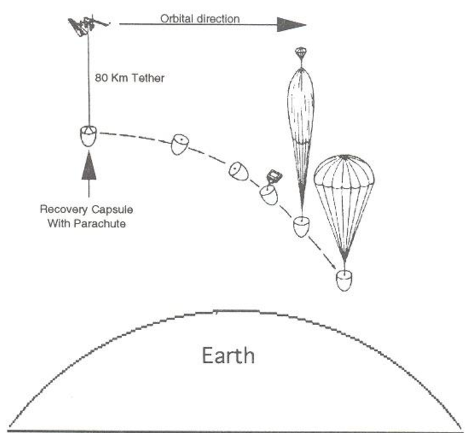

Figure 5. Tethered Return of Goods and Materials from Space Station

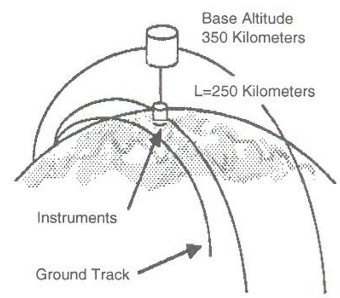

Figure 6. Tethered Satellite for Lunar Remote Sensing

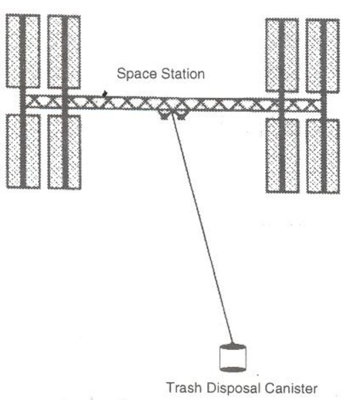

Figure 7. Space Station Tethered Trash Disposal System

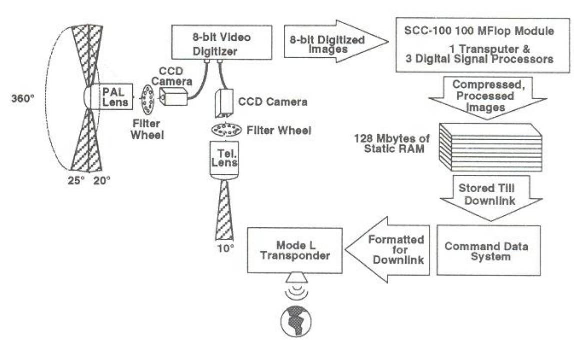

Figure 8. Space Station Tethered Trash Disposal System

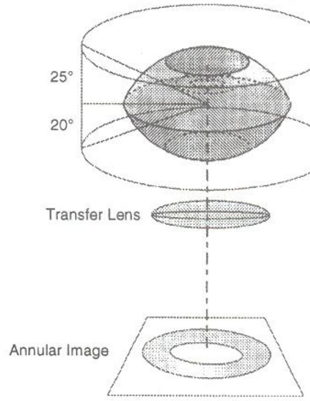

Figure 9. Panoramic Annular Lens (PAL)

Figure 10. Panoramic Image Taken at Alabama Space and Rocket Center

Figure 11. Earth Cuts Across the PAL FOV

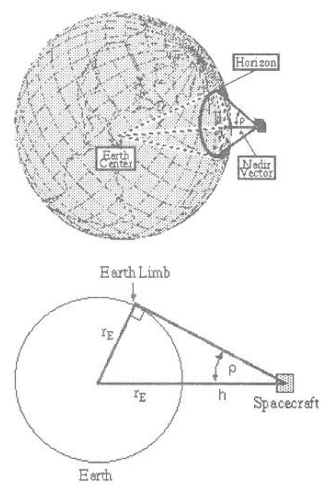

Figure 12. ρ = Earth's Angular Radius

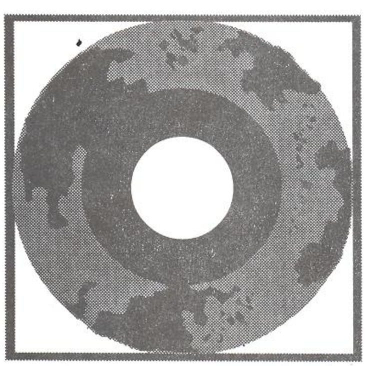

Figure 13. Earth When PAL is Pointed Zenith

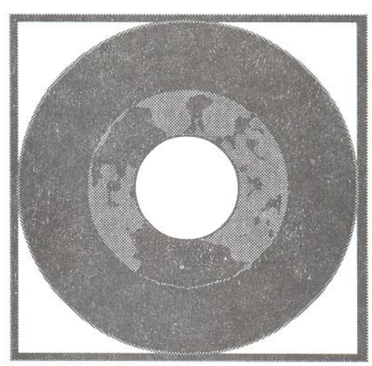

Figure 14. Earth When PAL is Pointed Nadir