CHEAP AURORAL TOMOGRAPHICAL SYSTEM (CATS)

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The Cheap Auroral Tomographical System (CATS) consists of a large constellation of small, disposable satellites in a near polar orbit. CATS is designed to collect stereoscopic views of the earth environment that will be used for tomographical and earth environmental research. Each satellite will be identical and constructed of high-grade commercial parts, thus significantly reducing the cost of design, fabrication and components.

The CATS constellation will be a significant step toward the demonstration and validation of the capability to develop, deploy and operate a proliferated system of small, inexpensive satellites. Additionally, CATS will gather valuable scientific data from the earth environment. This paper explores the possibilities and ramifications of such a system.

INTRODUCTION

The Cheap Auroral Tomographical System (CATS) is designed to collect stereoscopic views of the earth environment that will be used to demonstrate 3D tomographical reconstructions and perform earth environmental research. The main objectives of CATS are the following:

- *demonstration of space based sensor tomography*
- *auroral observation*
- *polar mesospheric cloud observation*
- *smog and other pollution observations*
- *seasonal change observations*
- *microsat constellation development demonstration*

CATS consists of a large constellation of small, disposable satellites in a near polar orbit. A main goal of CATS is to demonstrate the observation capability of a large constellation of small, light, inexpensive satellites. Each satellite will be identical and constructed of high-grade commercial parts, thus significantly reducing the cost of design, fabrication and components. Each satellite will be equipped with a wide angle camera, transceiver, control electronics and body mounted solar arrays. To reduce costs and simplify operations, there will be no active station keeping in CATS. An objective of CATS is to challenge the conventional wisdom that satellites must be very expensive to build and operate. The goal of CATS is to produce each satellite with a mass of less than 5 kg and maintain a minimal cost per satellite.

TOMOGRAPHICAL RESEARCH

One main objective of CATS is to provide stereoscopic views of the earth environment for the purpose of tomographical reconstruction and research. Tomography is the formal mathematical procedure for reconstructing an object from various line-of-sight images. Tomography is best known for its application to medical imaging where it has proved invaluable for evaluating X-rays, magnetic resonance emissions, and positron emissions. Some groundwork for applying tomographical techniques to airglow and auroral features has already been completed. Tomographical reconstruction techniques require multiple views of the source region of interest taken from many different directions. With a time varying source, the views, unlike a CAT scan, must be taken simultaneously.

The primary data are images of the aurora and polar mesospheric clouds. These data will be processed on the ground resulting in 3D imagery and models. The successful results of this application would be a further understanding of the aurora and northern atmospheric characteristics in addition to developing new tomographical techniques.

Various tomographical techniques, including the iterative and transform types, will be used in this project. The filtered back-projection technique is one such method that has been successfully demonstrated in other applications. Using the iterative Algebraic Reconstruction Technique (ART) with underrelaxation, successful tomographical reconstruction of 2D images has been completed at The Johns Hopkins University / Applied Physics Laboratory (APL). In short, ART reconstructs an object specified by some function f(X,Y), where f is an object of isotropic emissivity. The key to the ART approach is that the problem is reduced to solving a very large but sparse system of linear algebraic equations. Figs. 1 and 2 demonstrate the geometry of tomography. Fig. 3 shows some results of tomographical techniques[1].

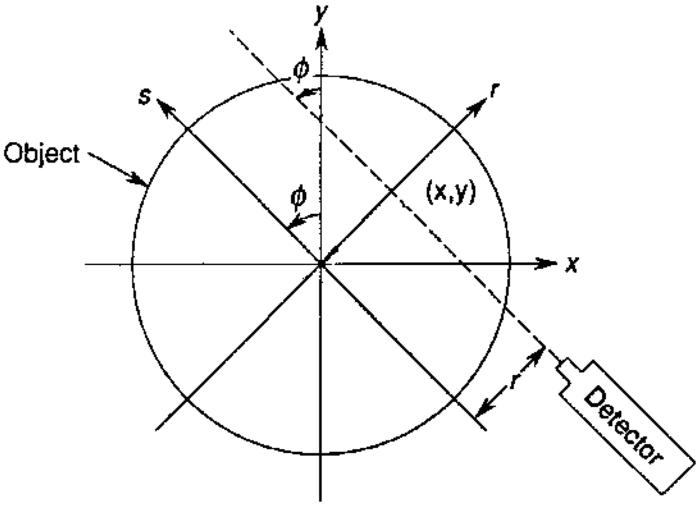


Fig. 1 Geometry of tomography - A point in the object has (x,y) or (r,ϕ) coordinates. The dashed line represents a ray-path. Projections are measured by the detector for all r and for ϕ from 0° to 180°.

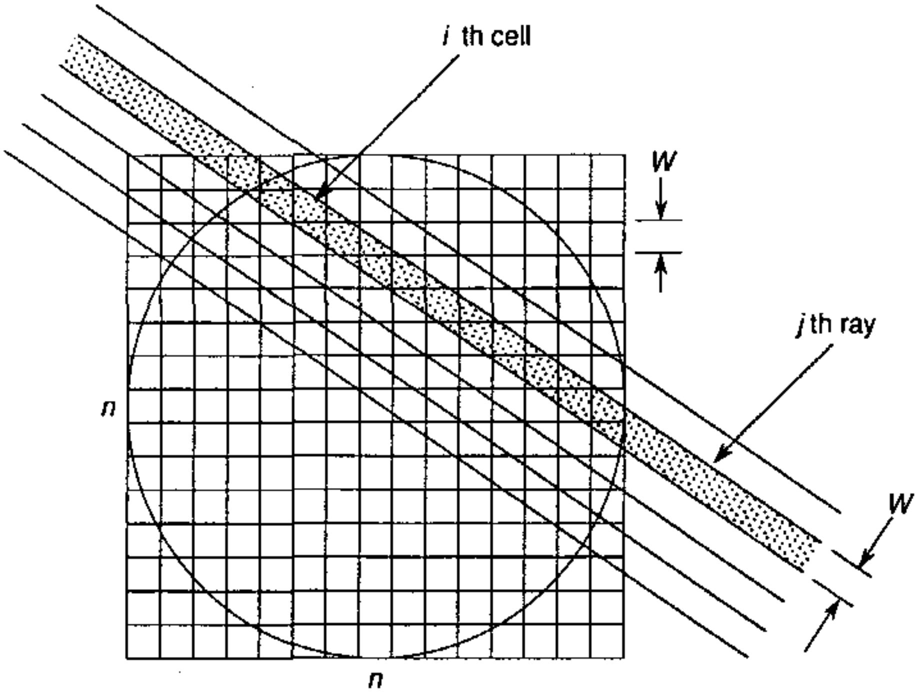
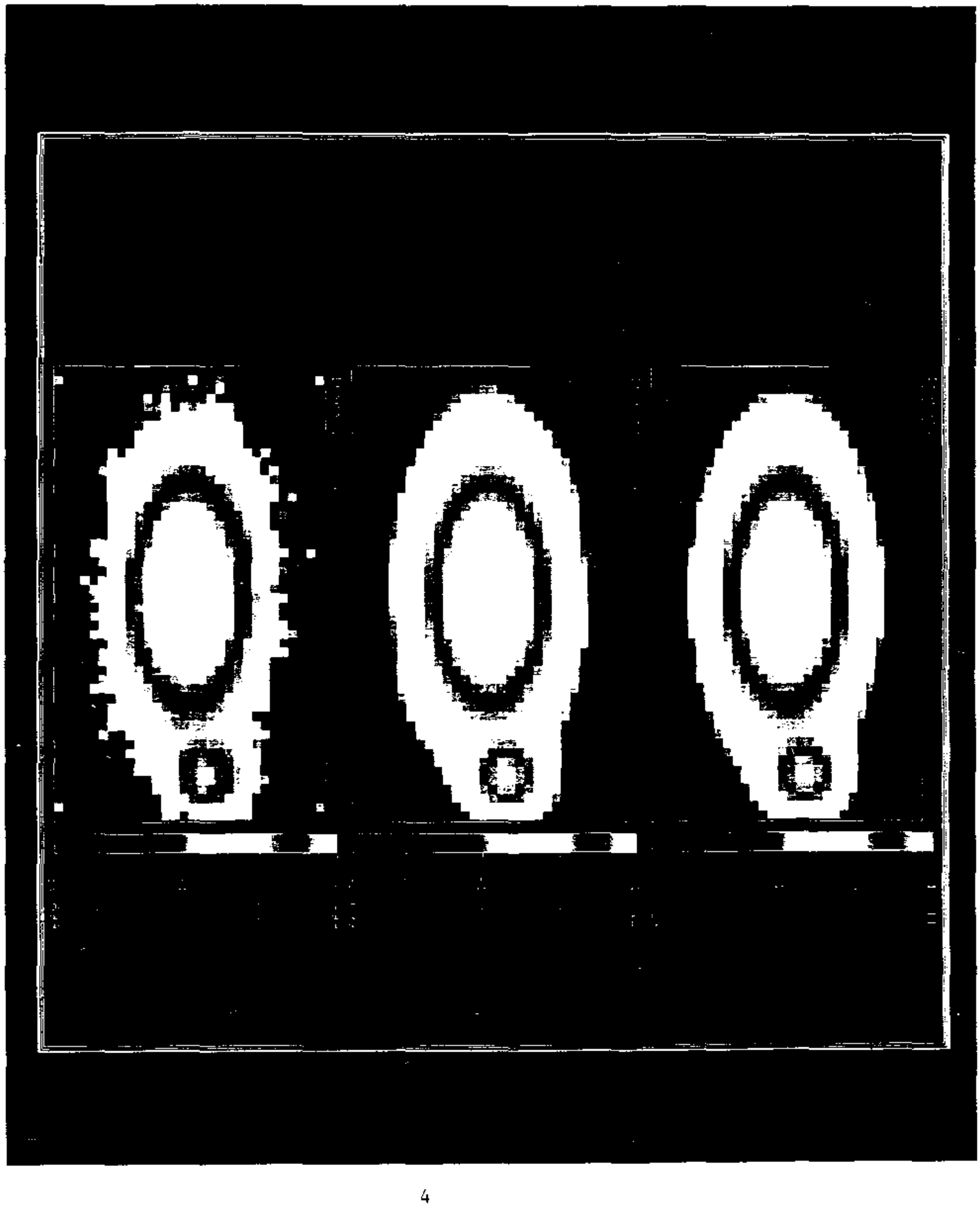


Fig. 2 Tomography with square pixel array. A finite-width ray-path is shown (shaded). The overlap of the i^{th} pixel (cell) with the ray-path is shown.

Fig. 3 Tomography results: Top panel - original object, with contrast of 5000 to 1 (logarithmic color bar). Center panel - reconstruction by tomography, no noise, showing excellent reproduction of original. Lower panel - reconstruction by tomography with substantial noise (see text). Principal structures of object are still recovered without significant artifacts.



The advantage of the ART method is twofold. First, it is known to exhibit excellent convergence properties. This characteristic is true even for cases of underdetermined (the system of equations being solved has fewer equations than unknowns) or overdetermined and inconsistent sampling data (equations are inconsistent because of noise and measurement errors). In all cases, the solution resulting from the ART method converges to a least-squares best fit solution.

The second advantage is that this technique can be easily extended to higher dimensions. Extension to 3D imagery can be accomplished by stacking along the Z-axis the various thin 2D (X-Y) slices to form the 3D tomographical reconstruction. The 3D object can be thought of as divided into slices like a loaf of bread. Each slice is separately reconstructed using the 2D tomographically constructed images. The 3D image is built up by stacking the slices on top of each other. Furthermore, due to its inherent flexibility, the ART method can be extended to objects that possess anisotropic emissivity properties, such as polar mesospheric clouds. Since polar mesospheric clouds scatter light in the forward direction of the incident ray of light only, stereoscopic images of these clouds could be used in tomographical techniques that are applicable to objects that produce anisotropic emissions. The successful application of tomography to objects exhibiting anisotropic emissions would be an important developmental step in the field of tomography and to environmental research.

ORBITAL CONSTELLATION

Due to tomographical requirements, a complete 4π steradian view of the earth would be ideal; this would be similar to a full earth CAT scan. A full earth scan would require a constellation of approximately 2000 earth pointing satellites. The full 2000 satellite constellation would provide immense amounts of environmental data from all latitudes of the earth that could be used in earth environmental studies. Due to spacecraft limitations, deployment difficulties and cost constraints, such a system may not initially be feasible. The minimum system that is acceptable is a 180 deg slice viewing of the aurora. Such a system would require approximately 60 satellites and could be used as a demonstration of the concept prior to the full 2000 satellite constellation development. The 60 satellite constellation will provide a complete viewing of the aurora and northern regions with all satellites in the constellation in the same orbit plane with average spacing of 120 km as shown in Fig. 4.

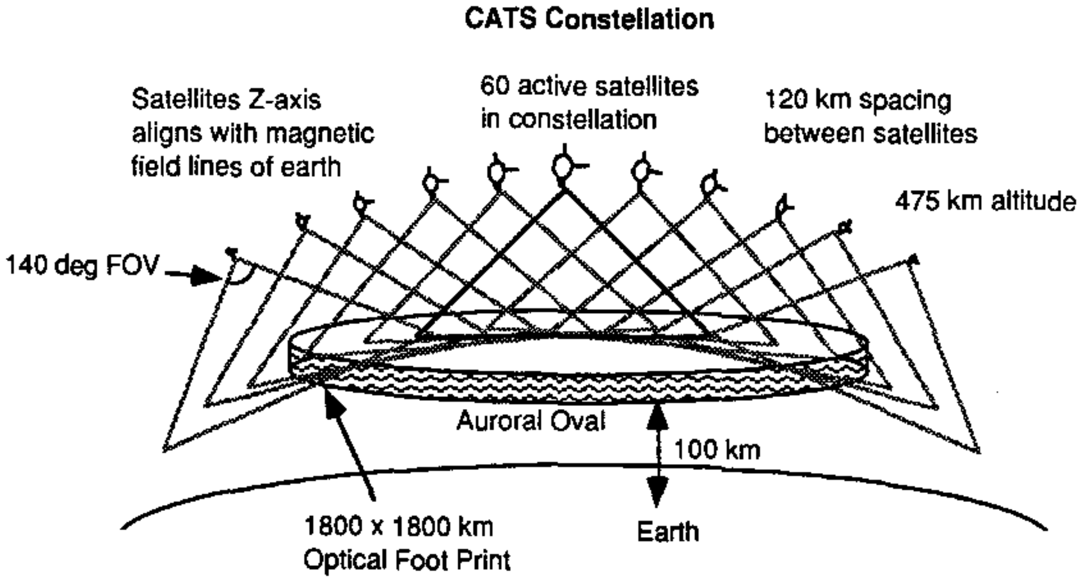


Fig. 4 Geometry of CATS Constellation

At the optimal viewing position, all satellites will view the auroral oval simultaneously. This size of constellation is required for two reasons: 1) to collect a sufficient number of images necessary to obtain stereoscopic views that can be used in tomographical and environmental studies, and 2) to tolerate a lower reliability satellite while maintaining a highly reliable system with multiple copies of each component, "graceful degradation". This will demonstrate the capability of large quantities of small and inexpensive satellites.

A polar orbit of approximately 86 deg inclination provides optimal viewing of the auroral oval. The ground traces in Fig. 5 shows the oval being sliced at various angles and different positions and widths[2]. The larger arrows on the bold track indicates satellite position and direction at one minute intervals. The slightly smaller arrows represent FOV boresight intersections of the 250 km altitude ellipsoid. The orbit demonstrated in Fig. 5 will provide a complete stereoscopic view of the auroral oval over the lifetime of the mission. This orbit also provides the ability to view the auroral oval during the winter months, and view northern cloud structures (particularly polar mesospheric clouds) during the summer months. This follows

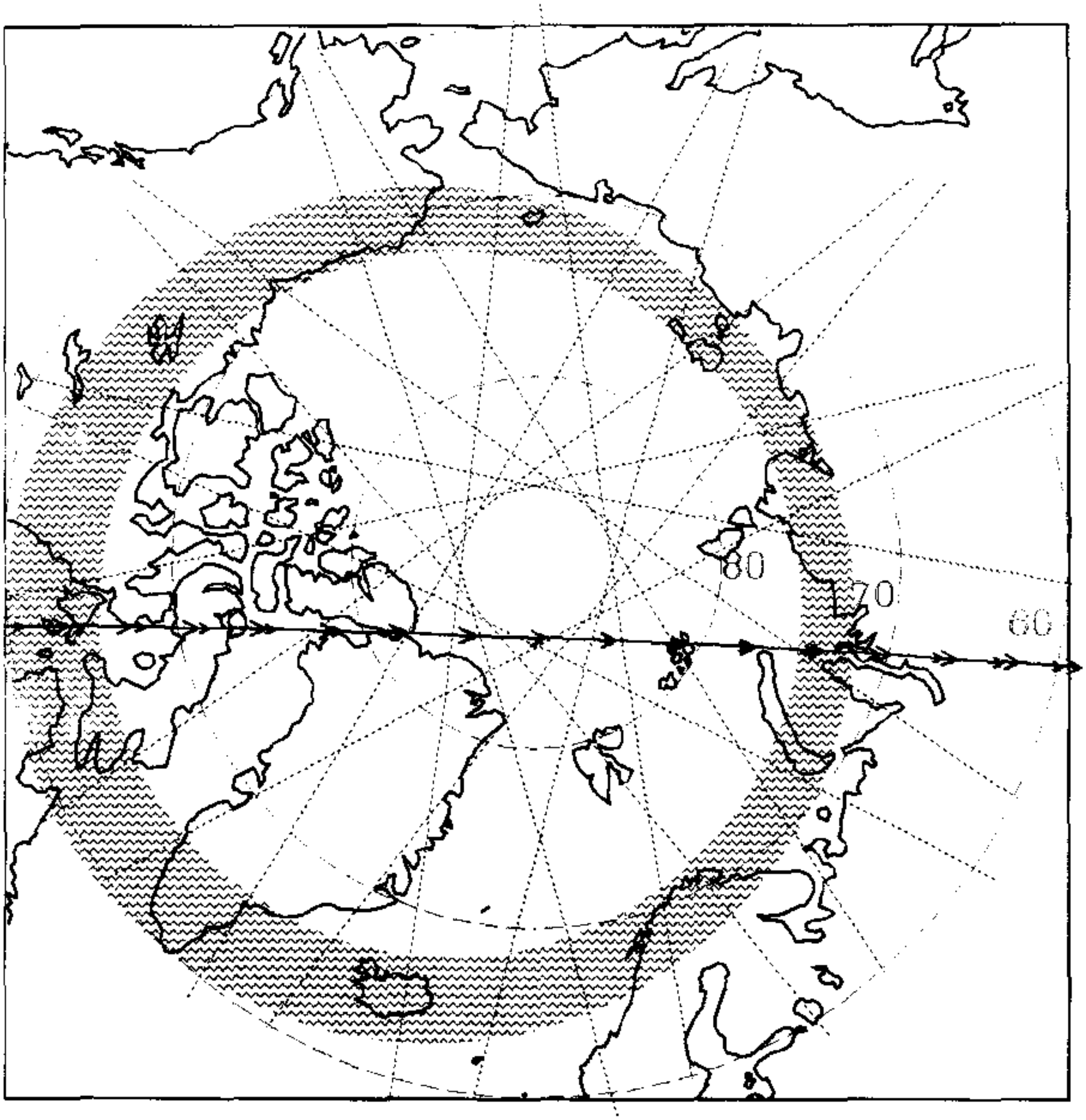


Fig. 5 CATS Satellite Ground Track over North Pole and Auroral Oval

the mission objectives by devoting a major portion of the mission to collect images exhibiting anisotropic emissions. The orbital lifetime of the satellites will be on the order of two years. A study of the orbit lifetime indicates the following results based on a 1 ft^2 cross section of the satellite with varying mass and altitude[3], the findings of the study are summarized in table 1.

Table 1
ORBIT LIFETIME STUDY

Mass (kg)	Altitude (km)	Lifetime
4	300	7 days
4	400	60 days
5	450	9 months
5	500	3.5 years
6	450	1 year
6	475	2 years
8	400	5 months

The final orbit will be low enough to limit orbital lifetime to two years. Therefore, the space environment will not remain cluttered with the satellites (which have no active station keeping) and any associated launch or potential collision debris.

There is a single ground station located at the U. S. South Pole base. Each satellite will pass over the ground station for approximately 11 minutes every orbit (see Fig. 5). During this time the images and telemetry data will be downlinked to the ground.

ATTITUDE CONTROL

Attitude control of the spacecraft will be accomplished using passive magnetic stabilization techniques. Magnetic stabilization of satellites was invented and demonstrated at APL in 1960. There is no active attitude control on the satellite. Permanent magnets will be placed on the satellite to align the +Z axis to point toward the magnetic north pole (southern polarity). Therefore, during the orbit, the satellite Z-axis will follow the magnetic field lines of the earth and perform two inversions per orbit. During the pass over the northern regions the satellite +Z axis (where the camera is mounted) will be pointing downward toward the geomagnetic pole. During the southern pass, the satellite -Z axis (where the satellite antenna is pointed) will be pointing downward toward Antarctica, where the receiving station is located. Thus, during the northern passes, the satellite will take images and store them on board, and during the southern passes, the data will be downlinked to the single ground station.

To damp attitude perturbations, several hysteresis damping rods will be mounted on the satellite to cut through the magnetic field lines. Thermal gradients across the X-Y plane will be eliminated by using solar torquing vanes. Each vanes will be constructed as part of a hysteresis rod, to reduce the weight requirements of the spacecraft. The vanes will rotate the satellite about the Z-axis. The four blade elements, painted black on one side, and white on the other, will rotate, like a radiometer, due to photon absorption and reflection. The resulting spin will provide a torque that will give a stabilized rotation about the Z-axis. A similar technique to this was used successfully on the AMSAT-OSCAR 7 and the AMSAT-OSCAR 8 spacecraft missions[4].

Attitude measurement is performed by an onboard magnetometer in conjunction with the images from the camera. Ground processing of the images and the magnetometer data can, in principle, provide the two reference vectors to completely determine the spacecraft attitude at the time of the image integration.

OPERATIONS

To obtain time fixed stereoscopic images all satellites must snap their pictures simultaneously. A timer on each satellite turns it on as it approaches the auroral oval. The satellite takes 50 pictures at 140 km distances (50 pictures over 60 deg = 1.2 deg/picture), which is about one picture every 20 seconds.

Due to oscillator drift, synchronization of the clocks on all of the satellites is required. Synchronizing the clocks will be done periodically by strobing a signal to the satellites as they pass over the South Pole ground station. This signal will be received by the satellites and the processor clocks will be reset. The drift in the oscillators is not significant over short time periods. Thus, all images would be taken at the same time which is required for the tomographical reconstruction.

IMAGING SENSORS

A potential imaging sensor and storage device to be used on the CATS constellation is the commercially available Sony video disk camera (or equivalent). The Mavica MVC-A10 has several qualities that make it a viable candidate. The camera can store 50 images on a 54mm X 60mm (approx. 2 inch) magnetic disk. This disk, constructed of magnetic powder, a binder and base film, is heat resistant and durable. The disk must meet the requirements of 585,000 total image writes (or approx. 12,000 writes per track), which is necessary for a two year mission. Once the images are stored on disk, they can later be downlinked during a pass over the ground station. Table 2 outlines the specifications of the camera[5].

Table 2
SONY MAVICA MVC-A10 CAMERA SPECIFICATIONS

Category	Specification
Weight	620g (includes nonessential packaging)
Dimensions	5-3/4 X 2-1/4 X 4-3/8 inch
Lens	15 mm (mount modified for various lenses)
Image Sensor	2/3 inch diagonal MOS (280,000 pixels)
Shutter	1/60 - 1/500 sec
Power	2.0 W peak
FOV	modified to 140 deg

The Field Of View (FOV) of the camera will be extended to be compatible with passive magnetic attitude control. The spacecraft pointing along the magnetic field lines is all that is required to obtain the desired images. When the images are dumped to the ground, they are retrieved from the disk and converted to analog FM signals via a control box and a data formatter. The data is then passed to the transceiver where it is transmitted to the ground station.

COMMUNICATIONS

The transmitter is a commercially available 5 W amateur radio 2-meter VHF transceiver. The signals are received by a single ground station at the U.S. South Pole base. Because there is no 2-meter traffic in this location, all 400 VHF channels should be available for use. This, of course, assumes that permission will be granted to operate in those frequencies. If this is not possible, a different transceiver can be purchased; although it will be more expensive, it will operate in the permissible frequencies.

Once per orbit, the satellite dumps its 50 images to the station. The 50 x 256 pixels x 256 pixels = 3.3 Mpixels of data are dumped over a 10 minute period at a rate of 5 kpixels/sec. The 5 khz bandwidth analog signal is fed into the audio input of the commercial 2-meter transceiver. The magnetometer and housekeeping data will be merged into the telemetry stream by the flight processor. The amount of housekeeping data is very small compared to the image data and will easily fit in the allocated space.

FLIGHT PROCESSOR

A flight computer is required to control the spacecraft. This entails resetting the oscillators, formatting telemetry data, and controlling the camera. An inexpensive reliable flight processor could be developed using the 87C51 class microprocessor. This is essentially a complete computer on one chip. It contains a CPU, 32 Kbytes of ROM, 256 bytes of RAM, 32 I/O pins, and a UART. Additional hardware required for an operational system would be an oscillator and some buffers. The cost for the processor hardware would be approximately $500, the weight approximately .2 kg and the power approximately .5 W.

POWER

The power allocations for each satellite is estimated in table 3.

Table 3
ESTIMATED CATS POWER AND DUTY CYCLE

Item	Power (W)	Duty Cycle (%)
Transmitter	5.0	17
Camera	2.0	33
Camera Controller	1.0	33
Data Formatter	0.5	17
Magnetometer	1.0	50
Microprocessor	0.5	100
Orbit Average Power	3.0	
Total OAP (67% Eff.)	4.5	

A brief study to find an inexpensive solar cell technology was undertaken to support the CATS satellite constellation[6]. The solar cells are a major cost driver of the system. Three cell types were investigated: 1. Crystalline Silicon (Si). 2. Copper Indium Diselinide ($CuInSe_2$). 3. Amorphous Silicon (a-Si).

Table 4 summarizes the solar cell study. It should be noted that the large differences in cost estimates may be due partly to the fact that two of the companies may have been thinking in terms of a "full blown" aerospace development program and the third was considering "off-the-shelf" terrestrial costs. The actual development scheme should lie somewhere in between these two philosophies, but will have to be closer to the second approach to achieve manageable costs. The assumptions made in this study are 3-4 W orbit average power requirements. For simplicity of evaluation, assumptions were a 2/3 ft^2 size box, or $4*2/3$ ft^2 = 2.67 ft^2 total area. For costing purposes it was assumed the total area to equal 3 ft^2. The worst case percent sun (@ 500 km) is approximately 62% and the cosine factor (averaged from -22 deg, the angle of the sun to the panel normal upon exit from eclipse, to 90 deg) is 0.7. This results in an effective area of .29 ft^2 orbit average, worst case. It is believed, from this study, that $CuInSe_2$ is the least expensive to mass produce.

Table 4
RESULTS OF CATS SOLAR ARRAY STUDY

Cell Technology	Module Eff. (%)	Power Area Density (W/ft^2)	Total Area Req. (ft^2)	Prod. Line Cost ($/W)	Total Cost per S/C ($)
Aerospace Silicon	10.7	13.5	3.0	667	27,000
Standard Silicon	10.7	13.5	3.0	467	18,900
$CuInSe_2$	8.0	10.0	4.0	3.0	120
Amorphous Silicon	5.0	6.3	6.4	100	4,030

For an initial launch of one or two satellites as a concept demonstration, it would seem prudent to use standard Si on half of the spacecraft and $CuInSe_2$ on the other half. This would provide an opportunity to qualify the new technology solar cell and still provide the ability to demonstrate other aspects of the concept in the event of an unforeseen failure mechanism relating to the new cells. For a full scale system, the only reasonable approach is to employ thin film, inexpensive cells with $CuInSe_2$ as the leading candidate.

A truncated pyramid design for the top of the spacecraft was incorporated to increase the effective use of the solar arrays. If the spacecraft is thought of as an omnidirectional array, then the optimal shape of the spacecraft would be a sphere, since a sphere has the highest ratio of projected area to total area. By adding a pyramid to the top of the box, it makes the spacecraft become more "sphere-like". After some analysis, it was shown that the pyramid configuration resulted in a savings in solar array area for the same amount of average power by 40%[7]. As mentioned previously, since the solar arrays are a major factor in the cost of the satellite, this is a significant savings factor on the system.

The solar array is required to generate 4.5 W of power. During the 35 minute solar eclipse, the worst case power usage is 2.71 W-hr. Over the lifetime of the mission, the batteries will go through approximately 11,700 cycles with an 83% reliability. Using standard cycle life versus depth of discharge curves, and allowing the battery depth of discharge to be 30%, a 2.71 W-hr / .3 = 9.03 W-hr total capacity is required. Using commercial 1.2 W-hr NiCad AA cells, 9.03 W-hr / 1.2 W-hr = 7.52 results in a requirement of eight cells.

The Orbit Average Power is computed using the power area density (W/ft^2) and the effective area of the satellite. For a cube of equal height and length equalling 9 inches, with truncated pyramids on each end, OAP = 4.8 W. Thus the satellite is a 9 inch cube with truncated pyramids placed on both the top (+Z axis) and bottom (-Z axis), see Fig. 6.

SATELLITE CONFIGURATION

The satellite consists of a wide angle camera, transceiver, control electronics, body mounted solar arrays, hysteresis damping rods, and various other components. As mentioned previously it is a 9 inch cube with truncated pyramids at the top and bottom. The configuration of the satellite is shown in Fig. 6.

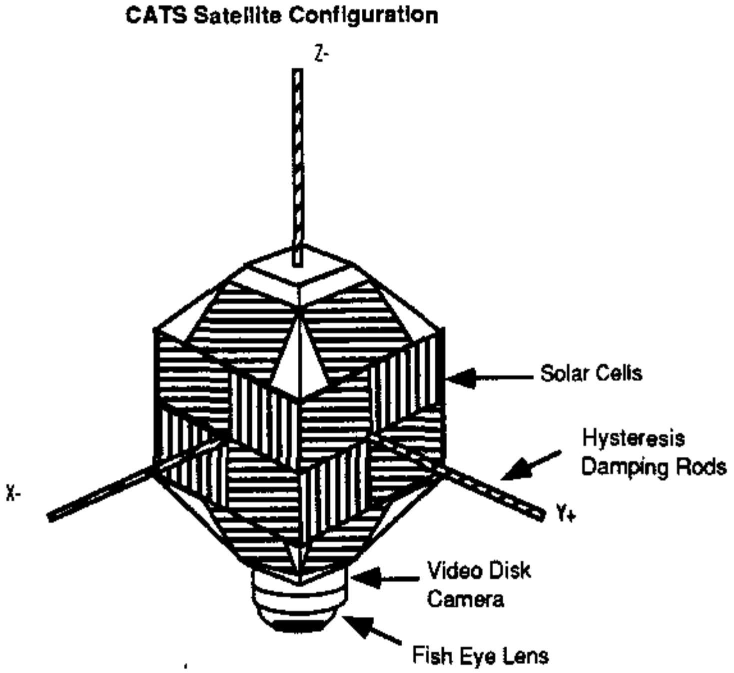


Fig. 6 CATS Satellite Configuration

Table 2 contains the total estimated budgets for each satellite.

Table 2
SPACECRAFT BUDGETS

Item	Mass (kg)	Parts Cost ($)
Camera & Controller	1.0	1,000
Transceiver	0.5	300
Solar Cells	1.0	120
Power Regulator	0.1	100
Modulator	0.1	300
Other Electronics	0.2	600
Structure	1.00	500
Magnetometer	0.25	1,000
Magnets	0.5	50
Battery	0.6	100
Total	5.25	4,070

The cost of each satellite is comprised of the following; Non Recurring Engineering (NRE), parts, fabrication, and integration and test. The engineering and design must be of a high quality to successfully build a large constellation of satellites. However, the NRE is one of the major costs of a satellite. The fabrication costs of the satellite could be minimized with the proper initial engineering. Inventive methods of testing, such as multiple satellite test configurations, could help maintain the costs of integration and testing. If the NRE could be kept under $5 million, the fabrication costs at $5,000 per satellite, the testing and integration costs at $2,000 per satellite, the parts at $5,000 per satellite and the constellation consisting of 2000 satellites, the per unit cost of each satellite would be less than $15,000. The entire cost of the 2000 satellite constellation would be $30 million. For a 60 satellite constellation, the per unit cost would go up to almost $100,000 and the entire constellation would be cost approximately $6 million.

LAUNCH AND DEPLOYMENT

The first phase of CATS would deploy a few prototype satellites. These satellites could piggy-back on the Space Shuttle, Ariane or some other launch vehicle. The 2000 satellite constellation proves more difficult. One of the difficulties is that all satellites must be deployed in the same orbit plane. A heavy lift rocket such as the Titan or Delta 2 could possible carry 500 satellites per launch to a low earth orbit. Therefore, with a deployment bus that would kick off each satellite at specified intervals, the 2000 satellite constellation could be deployed in four launches.

PROCESSING

Processing is done on the ground by a powerful computer system. Sixty satellites view the aurora at optimal viewing position in the initial constellation. Their images are combined by ART, filtered back-projection, or some other technique to produce three dimensional maps. This is a time consuming computationally bound task. For a few months of the year the satellites are in disadvantageous orientations to the sun. During this time the available power is diminished and the data rate reduced. Additionally, the processing can be done off line following completion of the mission.

CONCLUSION

The CATS constellation will be a significant step toward the demonstration and validation of the capability to develop, deploy and operate a proliferated system of small, inexpensive satellites. CATS will gather valuable scientific data from the earth environment. Three-dimensional models of the aurora will produce a better understanding of the physics behind the aurora and how it effects our environment. Tomographical development will enhance the understanding of 3D image analysis. CATS will provide valuable information for the furthering of space science, tomographical research, and environmental monitoring.

ACKNOWLEDGEMENTS

G. A. Herbert provided valuable analysis and support to the system and power concerns of CATS.

G. A. Heyler contributed to the orbit studies.

E. J. Hoffman reviewed and provided helpful ideas and technical advice for the system.

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