REMOTE ACCESS OBSERVATORIES
IN LOW EARTH ORBIT - A LOW-COST CONCEPT
FOR A SMALL SCIENTIFIC SPACECRAFT

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ABSTRACT

In parallel with the evolution of large observatory spacecraft such as the Einstein, Copernicus, and IUE, and the yet-to-be-launched Hubble Space Telescope and Gamma Ray Observatory, increasingly large ground telescopes are in construction which will allow ground astronomy to compete favorably with elaborate and expensive space systems in the quest for new discoveries. Sometimes overlooked in this pursuit of new discoveries, with the limited observational time on the space instruments, or the oversubscribed large ground instruments, is the recent development of smaller, low-cost robotic ground observatories designed for routine - but vital - collection of synoptic data. High-quality stellar observations are now being made by exploitation of new computer and detector technologies in unattended remote ground observatories, typically by modest aperture instruments tailored to the job. These instruments operate in modes similar to those employed in the observatory spacecraft.

Recent developments in the small satellite technology, some being reported at this conference, allow a reduced cost of payload delivery into orbit and suggest that another look is deserved at the 1960s' concept of small astronomical satellites, which would be operable by simple command systems to conduct monitoring of variable, flare, and cataclysmic stars, perhaps limited only to precision filter photometry or simple imaging in wavelengths not accessible from the ground. These would allow conduct of bread-and-butter astronomy at and accuracies wavelengths available only in space on objects identified by the larger research instruments, undertaking science too costly to pursue over long periods with multi-billion dollar systems.

This paper will explore small spacecraft provided with low-cost attitude systems (LCAS) for stabilization, modest telescope optics, and low-power communications and spacecraft computer sub-systems which could perform autonomous celestial acquisitions and photometric data collection.

INTRODUCTION

This decade has seen democratization of the space program, an opening of space science to new users and new applications made possible by the development of the Space Shuttle, through offerings of launches of private payloads under the Getaway Special Canister program (GAS-cans), and more recently the development of aircraft-assisted launches, which should allow elimination of part of the through-away booster costs. To prevent the USA from being dependent on the few large launch systems, DARPA and NASA have jointly developed the PEGASUS launcher to be carried to 10-km altitude beneath a B-52. This launcher will allow multiple small satellites to be orbited in a single mission, drastically reducing the cost of individual payloads.

Thus, with the resumption of Shuttle flights in late 1988 and the expected validation of the PEGASUS system in 1989, small science or technology applications payloads of 50- to 75-kg mass should have launch costs of \$50,000 (GAS-can on Shuttle) to \$500,000 (shared cost on PEGASUS with 6 or 7 payloads). Shuttle launches, typically at 28.5 degree inclination but potentially up to 57 degrees on infrequent opportunities, would allow circular orbits of up to 450 km altitude. The higher inclinations will be preferable for astronomical payloads, opening a larger fraction of the heavens to study during an orbit precession cycle. A PEGASUS launch would allow even higher inclinations of the orbit, but more importantly, would allow the orbit to be established at 740 km, assuring a longer orbital life and smaller drag disturbances to pointing.

The driver in exploitation of these low-cost launch systems will be packaging of viable science within the launcher envelope of size and weight. Here we investigate possibilities for a robotic observatory confined to a spacecraft of the NASA XSAT class (Cudmore, 1989), weight of some 68 to 70 kg and have launch configuration dimensions of 20-inches diameter by 19-inches height. Figure 1 shows one concept of such a small satellite, this one employing a nadir gravity-gradient boom to achieve a zenith-pointing stability of a few degrees by exploiting the slight gravity difference between the pull on the spacecraft body and the pull on the mass at the boom tip some 20 to 30 feet lower. Damping of the pendulum-like swings of this no-moving-parts system is effected by the hysteresis rods shown or some other magnetic interactions. A telescope could be contained within the body, supported in gimbals to free it from the librations. We will later consider another type of simple attitude stabilizer in conjunction with an astronomical payload. First we will consider the environment in which the payload must function and in which we seek to do science.

Since the science to be accomplished will drive the acceptable design, we will look first at small satellite science astronomical science, then at demands placed on systems for freedom from contamination of the optical elements, payload stabilization needed, etc.

ASTRONOMY BY SMALL SATELLITES - AN EXTENSION OF GROUND NETWORKS.

The approach to astronomical observations with low earth–orbit satellites as described in this paper is unique largely because of the use of a technology which has been developed for use on ground–based telescopes. The technology contains two new aspects, a) the hardware and "firmware"called Remote–Access Automatic Telescopes (RAATS) and b) a software interface, which is called the Automatic Telescope Instruction Set (ATIS).

Ground–based astronomical telescopes have traditionally been operated manually by a human operator, even when computers are included to a substantial degree in the system. The human operator often is the astronomer, but the telescope is often operated by a technician in the case of the largest telescopes. The astronomer operates only the instruments which make the actual measurements.

A number of attempts have been made to automate telescopes and their associated instruments, as has been described by Genet and Hayes (1989). When this is done, no human operator is present during the observations, with a resulting increase in efficiency, consistency, and effectiveness.
A further advantage is that the astronomer can work from the home campus rather than travelling across the country to performing routine operations better done by a computer, and wasting time waiting for clouds to pass.

Similar advantages can accrue when full automation, as developed for RAATS, is applied to operation of an astronomical telescope in a low–earth orbit (LEO) satellite. The purpose of this section is to describe the approach taken to automation of ground–basedtelescopes, and modifications which will be needed to adapt it to use in a LEO satellite.

Ground–Based Remote–Access Automatic Telescopes

The successful implementation of fully–automatic telescopes, and the long–term operation of them in routine astronomical observations, has been achieved by the Fairborn Observatory, in Arizona. Based originally upon a design by Louis Boyd and Russell Genet, the first automatic telescope has made photometric observations for six years. The telescope, first operated within the city of Phoenix, was moved a few years later to Mt. Hopkins, south of Tucson. Mt. Hopkins is the site of the Fred L. Whipple Observatory of the Smithsonian Institution (builders of the first Orbiting Astronomical Observatory, OAO–1), and of the Multiple–Mirror Telescope Observatory, an excellent observing site. The original automatic telescope has since been joined by two others, and four larger ones, of 0.75–meter aperture, are under construction. The first of these will begin operation in September, 1989. (Figure 2).

In order to make the operation of automatic telescopes flexible and efficient, a new approach to control by the astronomer was taken with the new generation of telescopes now coming on line. In this new approach, the telescope observes according to an ASCII text file sent over ordinary phone lines at some time before the beginning of the night of observation. The file contains enough information to keep the telescope operating for a full night of observation, and even may keep it observing for weeks or months, if appropriate. The file does not contain the specific commands which actuate the telescope, operate the detecting instrument, or condition and store the data. It contains only the objects to be observed and the type of observations to be made. The resulting observational data are written to an ASCII text file, and may be transmitted the next morning, or months later, again over ordinary phone lines, back to the observer.

The ASCII text file sends instructions to the telescope in a format called the Automatic Telescope Instruction Set (ATIS), which has been described by Genet and Hayes (1989), pp205–26. ATIS resembles a programming language in some ways, but has some profound differences from the conventional idea of a programming language. One of these reflects the fact that the computer which controls the telescope and instrument is programmed with some "intelligence,"such that an ATIS input file is not a rigid program telling the telescope what to do moment–by–moment through the night. On the contrary, the control computer, itself, determines what to do during the night.

A night of observation normally consists of observations of a large number of objects, with motions from one object to another in between. Usually, the observations of an object, say a star, include some other observations close in time and position to the object. For example, observations are usually made of a patch of sky, to determine the background, and of one or more other stars for comparison purposes. Comparison stars are observed in order to determine, and eliminate, changes in the transparency of the earth's atmosphere and the sensitivity of the detector. Thus, an observation of a single object is actually a set of observations which is called a group.

The ATIS input file contains, among other information, a list of candidate groups to observe during the night, and the control computer, itself, selects which group to observe at any given time during the night. The order of the groups in the list is, for ground telescopes, immaterial with the selection being determined by a set of criteria which will be described in the next section. As a consequence of this scheme, the choice of groups to observe is determined locally and intelligently, without the need for a rigid program, and without "real-time" input from the astronomer.

The ATIS ASCII text file also contains information telling the telescope and instrument how to make the observations, such as integration times, which filters to use, and so forth. Also included are information needed for reduction, which is passed through so the output file will be self-contained.

The key, then to the flexible and efficient operation of the ground-basedRAATS is the set of criteria by which the control computer makes the selection of the next group to observe.

Group Selection Criteria

-At any given time during the night, the control program searches through the list of candidate groups to select the next one to observe. Seven criteria are used, and each candidate group entry in the list includes values of parameters used by the criteria for selection. Not all are applicable to our space observatory; they are given for completeness and to allow insight into the transformation of ground criteria to orbiting criteria. The criteria are as follows:

1) The beginning and ending date for the observation, given as the Julian Date (an astronomical method of specifying a date in days, beginning at 4713 B.C., and using noon as the beginning of each day). The group can be observed at any time between the beginning and ending dates.

2) The beginning and ending time for the observation, given as the Local Sidereal Time (an astronomical method of determining time according to the position of a point on the sky, rather than the sun, as the basis). The group can be observed at any time between the beginning and ending times.

3) The specification as to whether the observation can be made with the moon up, down, or that the position of the moon doesn't matter. The location of the moon is important, because it greatly increases the background light. Some observations, such as of very faint objects, cannot be made with the moon up.

4) The specification of the priority of the group. The priority is a number from 1 to 99, with 1 being the highest priority. When the control program must choose between two groups which are otherwise equally selectable, it chooses the one with the highest priority.

5) The specification of the number of observations. A group may be observed more than once during the night, and the control program keeps tract of how many times it has been observed.

6) The nearest-to-end-LST (NELST) rule. As noted above, the second criterion specifies the beginning and ending times, between which the group is to be observed. Two groups may be equally selectable, but the current time may be closer to the ending time for one than the other. The closer one is selected, in order to minimize the possibility that it might be missed.

7) The specification of a probability. The probability is compared with the results of consulting a random number generator, with the result that the group will be observed less often than once a night, but randomly.

As shown by Genet and Hayes (1989), these criteria are sufficient to completely structure a night, and yet not cause the problems that a rigid program would create. For example, these automatic telescopes are actually automatic observatories, in which the protective structure (the roof, the building housing the telescope, all supporting subsystems) is controlled automatically. If it clouds up during the night, observations stop. If it starts to precipitate, the roof will close. If conditions return to observability, the observations can re-commence.

A rigid program could not account for such an eventuality, whereas the present scheme has no problem. The time it takes to slew from group to group differs according to their locations, and the time it takes to observe each group can differ according to the integration times specified. These differences would be cumbersome to account for in a rigid program, whereas they are accommodated in a very straight forward way in the scheme devised under ATIS. This departs from the operating philosophy adopted for the Hubble Space Telescope where nearly every command must be assembled and sent to the HST during one of three or four contacts each day. Without contact, the observations stop. Under ATIS observations continue until commanded.

The Application of ATIS to LEORAATS

The system which has been developed for ground-based telescopes, described above, can be adapted to the operation of a LEO satellite containing a small astronomical telescope. ATIS can be adapted to the differences in the type of observations made and the mode of observing with few problems. Of greater concern is the adaption of ATIS to the selection of groups to observe and the slewing to and acquisition of the group. The dynamic conditions of a telescope contained in a satellite are very different than one located on the surface of the earth, and they must be carefully taken into account in the adaption of the control software. Here we indicate roughly how ATIS can be modified to take into account the new dynamical and environmental conditions, but it should be noted that considerable development work remains to be done.

In the operation of the LEORAAT, the same basic approach will be taken as with the ground-based RAAT, in that a file will be sent to the satellite which will keep it busy observing on its own, for an interval of time which will depend upon the type of observations to be made. The file will include a list of candidate groups, to be searched at completion of the preceding observations, according to a set of criteria for group selection. The on-board computer will run the control program executing the ATIS group selection process, so this function will be local to the satellite. As with ground-based observing, we will refer to a group, rather than a star or an object, since observations additional to those made on the object of interest must be made. For example, observations of the background must be made, even though scattered light outside the earth's atmosphere will not be nearly as large as from the ground. There will be scattered light from contamination and from the residual atmosphere in the satellite's environment, from zodiacal light, and background due to faint stars and galaxies. Comparison stars must be observed, in order to eliminate changes in the sensitivity of the instrument. Thus, an observation of a star will still include a group of observations.

The selection criteria for group selection must be very similar, in principle, to those used in ground-based telescopes, but different in detail. The most significant change will be a set of criteria which will replace the moon criterion, 3), above. Criteria must be developed for the position of the satellite in its orbit relative to radiation belts, the satellite zenith relative to the moon and the sun, and according to the time in the power cycle of the satellite. The length of the slew to a given group may impact the power cycle, and certainly will affect the schedule of observation times, so it may become a selection criterion. The number of reads of the CCD detector in a given time will affect the power cycle, and the number of reads in a given time decreases when fainter objects are observed, because of their longer integration times. Thus, the brightness of the objects in the group may become a selection criterion. As in the case of ground-based RAATS, windows in date and time would be specified, as would be the priority, number of observations, and a probability. The NELST rule would still be used.

As a result of this scheme, the satellite control computer will be determining the observing program as it goes along, according to flexible, but well-determined, criteria which adequately reproduce the conditions which must be taken into account. The astronomers using the LEORAATS will not, themselves, have to work out the observing program in detail, resulting in an increase in the efficiency of use of their time. It is very likely that it will result in an increase in the efficiency with which the time of the LEORAATS is used, also.

SCIENCE OBJECTIVES FROM A SMALL LOW-EARTH ORBIT OBSERVATORY

The most advantageous areas in which to exploit astronomical observations from space are in:

1) variations of observables with time, unhindered by naturally enforced breaks such as day-night, clouds, etc. and

2) exploitation of wavelength regions inaccessible from the ground.

Until now the primary and almost exclusive emphasis has been in area 2, with only token attention to area 1. Only after a spacecraft has outlived its original exploration mission has time been assigned for lengthy synoptic observations of a few of the most enigmatic objects.

Satellite observatories (e.g., the Orbiting Astronomical Observatory or OAO, the International Ultraviolet Explorer or IUE, and the Copernicus satellite) have been spectrophotometric instruments with primary or exclusive applications in the ultraviolet - below about 3000 Angstroms. Observers know quite well that spectral observing is far less affected by weather, the day-night cycle, and other problems of ground-based astronomy than is photometry, yet low-level temporal photometric variations (exceedingly difficult from the ground) have, ironically, been the ones neglected in space astronomy. Only in some studies of variability of the solar luminous output have the repeatability of orbital photometry been put to the test, with excellent results. This inversion of application can be justified on the basis of the absolute impossibility of doing far-UV spectrometry from the ground, while ground-based temporal variation is only very difficult – not completely impossible.

It is now time to restore balance to our observing programs and gather the benefits of photometry from space. Models of astrophysical systems, e.g., pulsating stars, interacting binary stars, etc., are effective suggested and tested when both spectral and temporal photometric measurements are available. To date only rudimentary results on variations in brightness, color, and polarization with time have been obtained from space.

Polarization Measurements

Before addressing observations of specific kinds of objects, attention should be given to an observing mode which is natural to include with photometric telescopes. This is stellar polarimetry, on which recent progress has been made by several groups (especially Kemp and associates). Many poorly understood mechanisms are probably responsible for the observed polarization curves, but it is interesting to note that the long-sought limb-polarization effect (Chandrasekhar, 1946) due to electron scattering in hot stars may well have been detected in Algol by Kemp, et al. (1983). Observations of this and other effects from space, without intervention of the earth's atmosphere as a scattering medium, should make practical a whole new area of observation and theoretical modeling.

We will treat only three brief applications here and refer the reader to other summaries.

Variation of Astrophysical Observables in Time

The value of continuous coverage – unbroken by weather and the daily cycles of sunlight, moonlight, and object visibility – is a singularly important advantage of space-based telescopes. Improved coverage is particularly needed when the period or time scale of the variation is of the order of a day, and problems also arise at small integer multiples of a day. An important related problem which must be recognized is that of coordinated observations of two or more types. Certain astrophysical problems require for example, simultaneous photometry and spectroscopy. It is easy to lose sight of this issue. Because such coordination is so difficult to realize from the ground alone, it is seldom even attempted. The probability of successful observing is a product of several factors (probability of good sky conditions, probability of source visibility at given longitude, probability of absence of sunlight at a given longitude, probability of absence of excessive moonlight, etc.).

The combined probability is small for each kind of observation, and when two probabilities are multiplied together, the overall probability is typically so small that one rarely even makes the attempt. Moreover, it is not sufficient for things to go well on one night, as many nights of observing are required for most such problems. However, it is important to note that it is the photometric part – not the spectroscopic – which is by far the more sensitive to departures from ideal conditions, so that a coordination of space photometry with ground-based spectroscopy has an much higher likelihood of success than would the reverse case, or the case of all ground-based observation.

One of the great triumphs of modern astrophysics has been the understanding of pulsation in Cepheid variables. Not only do we know that the pulsations are driven by an opacity-linked valve mechanism in the ionization zones of the stellar envelope, but computer models reveal the relative importance of the helium and hydrogen ionization zones and are able to predict details of the light and radial velocity variations rather well. While some quantitative issues remain to be worked out, the phenomenon is well understood, and we have a marvelous handle on stellar evolution. Here, surface phenomena tell us about the invisible insides of these stars. In retrospect, this progress has been possible because Cepheid pulsations are of large amplitude (for example, in both light and radial velocity) and in most cases the periods are such that observations are not undermined by the diurnal cycle, so that ground-based observations of fully adequate accuracy can be made. Measurements interrupted by the shorter spacecraft orbital periods will be less aliasing for this research.

Matters are not so favorable with other kinds of pulsating stars. For example, there are the multiple periodic stars of the Beta Cephei and Delta Scuti types. In these stars, successive cycles change in behavior, and the small amplitudes and periods of unfavorable observation make it difficult to follow these variations in as full detail. Typically, with a period of five hours, for instance, one cycle is observed, and then at least the next four are missed. From space many successive cycles could be observed continuously if the spacecraft can be operated into the continuous viewing zone near the poles of the orbit, and the basis for developing theoretical models would be greatly strengthened. Of course, the use of the IR and UV regions will also help. Dedicated photometric telescopes in orbit will be especially efficient and cost-effective in gathering the needed light curve and color curve data.

The pulsations of white dwarf star are on a very short time scale (tens to hundreds of seconds). These are thought to be non-radial pulsations of the gravity type (g-mode). In principle, should it become possible to understand them fully or even essentially, these constitute a powerful probe of white dwarf structure. However, at present, we know only a very small number of white dwarfs with detected pulsations. Discovery of such pulsations should be aided considerably by observations in the far ultraviolet because they are hot objects and most of the flux is at short wavelengths. Still another factor is the high accuracy of photometry from space. Thus all three detection factors strongly favor space-based over ground-based photometry, so that a major improvement in the threshold for discovering white dwarf pulsations can be expected. The reader is referred to a symposium proceedings by ESA.

Astrophysics: Near Infrared Observations

Important progress is waiting to be made in infrared light curves of several kinds of binaries including the RS CVn, Algol, and W Serpentis type systems. The RS CVn stars, named after the first-discovered prototype, are heavily covered with magnetic starspots, presumable similar to sunspots, but far larger and more numerous. Light curves in the IR (supplementing those at shorter wavelengths) will provide the long baseline in wavelength which makes it possible to measure spot temperatures independent of spot areas. If one observes over only a short range of effective wavelength, those parameters are very highly correlated.

For Algol type binaries, where one star eclipses the other, IR light curves will determine the properties of low-temperature sub-giant secondary stars For example, in Algol itself, the sub-giant contributes only about 2 percent of the flux at visible wavelengths, and is thus nearly invisible except for its eclipses of the hot main sequence primary. At 1.6 microns in the IR however, the sub-giant gives nearly 10 percent of system light so that, for example the laws of gravity darkening would be measurable, given an IR light curve from space. This idea has been around for several decades, but its realization is been delayed by difficulties in ground-based IR photometry.

Multi-wavelength observations

The unique capabilities of LEORAAT's can be applied to a variety of problems relating to binary systems of extreme astrophysical interest, whose analysis requires observations from multiple passbands, including one or more denied to ground-based observations. A straightforward example is UV photometry in combination with visual and near IR photometry taken in space or on the ground to detect hot companions to cooler giants and supergiants. In the case of the Zeta Aurigae eclipsing binary systems, a K-type supergiant eclipses a compact B dwarf. During partial eclipse the B-type star acts as a nearly point-source probe of the supergiant's atmosphere, and the duration of the eclipse depends upon wavelength. Much work has been done on these systems from the ground, but a LEORAAT would provide higher precision and the extension into the UV. Additionally, spectrophotometry of emission lines in the UV will allow measurement of the atmospheric characteristics of the K-star. Much new information is obtained when the short-period eclipsing binaries are observed in the UV as well as in the visible; the value of UV observations has been shown with IUE, but the amount of observing time available has limited progress. A broad class of binary systems have the common characteristic of a cooler, higher-luminosity star losing mass to a hotter dwarf, subdwarf or white dwarf, with an attendant accretion disk. The complexities involved in understanding these systems are great, but observations with IUE have shown the extension of the observations into the UV can add much information, particularly from the measurement to emission lines from the disk. A LEORAAT could perform [spectro]photometric observations of much larger numbers of such systems with UV coverage so that the hotter companion can be observed; it is usually masked by the cooler star in ground-based observations. Examples of such systems are the symbiotic stars, and the cataclysmic variables.

The LEORAAT would present the opportunity to observe many of the prototypical bright eclipsing, eruptive, pulsating, and spotted variables over a very broad wavelength range, either from space or in collaboration with ground-based telescopes. In doing so, information would become available which would greatly enhance our physical understanding of these important objects.

THE MOVING PLATFORM

At a height of 450 km the spacecraft will advance along the orbit at a nearly uniform rate of 3.85 degrees per minute (231 arc-sec/sec), some 15 times the rate normally encountered in ground telescope pointing systems. One simple strategy for celestial pointing would be to operate in a zenith-pointing mode, scanning the heavens at orbital rate. An orbital rate scanning mode was used in the early Orbiting Astronomical Observatory (OAO I, 1969) for its survey mode and more recently for the Infrared Astronomical Satellite (IRAS, 1983) to map the sky in four long-wavelength infrared bands. This allows only brief measurements of any specific object, useful only for surveys. Such initial mappings of the sky are now complete at almost every wavelength when one looks at the data from OAO, IRAS, IUE, Copernicus, Einstein, and the SAS and HEAO series (Small Astronomical Satellites and High Energy Astronomical Observatories). These latter spacecraft were the initial surveys in the X-ray region where nothing was known and scan-mode operations vital for future science. Since the spade work is completed, we face the challenge to design for the conduct of science, not surveys.

To measure with adequate accuracy a significant number of celestial sources of interest, we will need observing times of one second or more to achieve 0.1% precision, even with an aperture of 0.5 meters. One could rely upon a fixed focal-plane mask, allowing the star to drift through the field, as is done in meridian observations in radio astronomy. However the mask would need to be some 4 arc-minutes in length for each second of integration, allowing too many nearby confusing objects into the field-of-view. Better spatial discrimination will be needed, either by specific pointing of the spacecraft, pointing of the telescope independently of the spacecraft, and/or "pointing"the focal plane independently of the telescope. This latter task could be through moving optical elements or by a technique called time-delay integration, where the image location within an area sensor is followed by electronic or software processing to co-add the brightness in multiple readouts of the sensor.

We will not discuss these various options here but move on to define a spacecraft which could provide an adequate platform for stellar photometry, the measurement of a star's brightness in one or more standardized wavelength bands. At this point it should be noted that the discussions of dwell time on a given program object, to get adequate observing statistics, presuppose that the object has been acquired. The other obvious simplicity allowed to the early survey space observatories is that they measured everything above their noise threshold; only after the data were in the computer did they undertake finding where they had been looking. When one pursues a specific program object, one must send the telescope to its known position - and recognize that the object found is the right one.

Target Acquisition

Acquisition of a star by a ground telescope can be entirely automatic if the mechanical and optical systems are adequately referenced to the earth itself and to time. The earth's pole and the continents move only slightly and very slowly. Updates to Universal time are made only every 2-3 years, and then by only a single leap-second. Spacecraft orbital locations require constant measurements. Post-measurement fittings to orbital observations normally have uncertainties of large fractions of a kilometer, and predictions of where it will be are typically in error by 3-5 km in along-track location, even when being tracked aggressively. This translates into uncertainties of the celestial location of spacecraft zenith of 2-3 arc minutes (!), aggravated by the daily changes of atmospheric density at orbit height. We must be prepared to spend part of each observational opportunity in a finding and acquisition mode which forgive such uncertainties. How can we configure a simple spacecraft to do the job?

We must employ a sensor, and a telescope, with adequate field-of-view to encompass the pointing uncertainties and, in addition, provide autonomous capability for the sensor system to recognize the program star or at least a near-by navigation star. This problem has already been solved at a simpler level by the Boyd CCD in-memory spiral search device (Genet and Hayes 1989, pp148-51), where an image of the celestial field expected to contain the object near its central region is searched for the target star in software to determine the required repointing commands.

Attitude Control System

The attitude determination and pointing system for our small astronomy platform must regularly perform three essential functions:

1) attitude determinations of the spacecraft and telescope.

2) orientation of the telescope field-of-view toward the selected region of the celestial sphere.

3) inertial stabilization of the telescope field-of-view for the duration of the observation.

Two general configurations can be considered. In the first the platform attitude control system provides primary stability; the telescope assembly is mounted in gimbals. It may also contain moving internal mirrors for accurate centering of the instrumental field-of-view. In the second possible configuration the telescope is rigidly mounted to the platform, and all pointing motions are performed by the attitude control system.

Table I provides a qualitative comparison of the general characteristics of different configurations for several platform stabilization implementations, a gravity-gradient stabilized platform and two types of momentum bias

TABLE I. SOME GENERAL PLATFORM STABILIZATION CHARACTERISTICS

STABILIZATION METHOD	AXIS POINTING MECHANISM	ADVANTAGES	DISADVANTAGES
Gravity Gradient	Two-axis large-angle gimbals for telescope assembly	Quiet. Relatively simple, passive.	Uncertainty in pointing. Residual libration motions. Complex pointing mechanisms. Limited pointing range.
Momentum Bias, One Wheel	One-axis large-angle gimbals for telescope assembly. Pitch rotations controlled by ACS	Simple ACS. Altitude knowledge.	Requires one-axis pointing mechanism for telescope. Limitations in pointing range.
Momentum Bias, Two Wheels at right angles	No gimbals. Spacecraft ACS controls rotation.	Full FOV maneuverability through celestial sphere. Altitude knowledge. No mechanical gimbals.	Relatively sophisticated ACS control algorithms. Larger power requirements.

systems. The actual choice of an optimal configuration will require a trade-off analysis taking into account the desired pointing accuracy and stability, the desired effective sky coverage, required or wanted maneuvering characteristics, power, dimension and mass budgets, and cost.

The different types of systems may require a fine-pointing method to center and stabilize the field of observation after maneuvering the spacecraft or the gimbals to the desired orientation. The optical detector array at the telescope focal plane could provide the pointing information directly for the adjustment of the gimbals or secondary stabilization mechanisms as well as to the spacecraft attitude control system. Other payloads might need conventional star trackers for such a function, but an astronomy satellite offers use of a better sensor with only minor complication of the payload. The design of the focal plane and the of the fine control loop, imbedded within the coarse control, is an area needing careful study, both to achieve the required performance and to avoid unduly complicating the science modes.

The width of the field-of-view can be such that an electronic compensation of the pointing error might be possible. The star images could be recorded wherever they moved in the field-of-view and subsequent integration of the image light would then account for the image motion and rotation, effectively image-motion compensation by signal processing. Coarse control achieving 0.5-degree pointing might be sufficient for scientific use of an array sensor of 2-degree square dimensions.

For a very small satellite of the "GAS can" size, a fixed telescope mounted on a momentum-bias stabilized platform can provide a effective solution. Two reaction/momentum wheels canted at 90 degrees are sufficient to provide full sky maneuvering capability. A compact system of that type based on existing instrumentation typically includes two scan wheels (combinations of momentum/reaction wheels with infrared optical scanners providing pitch and roll attitude measurements), three magnetic torquers, a three-axis magnetometer, and a control electronics assembly. A variant of that system could include one simple wheel and only one scan wheel.

Control of the wheels is based on the pitch and roll measures provided by the infrared scanners included in the wheels. Momentum management and nutation damping are performed using the magnetic torquers. In a fine pointing mode control of the momentum wheels can be transferred to a fine-pointing algorithm using star-position information provided directly from the payload telescope.

What is proposed is that the spacecraft will be actively controlled in attitude, perhaps using a system called LCAS or "Lucas" Scanwheel (TM), a device which provides active control in two axes and stability in the third. Figure 3 shows the concept of the wheel/scan mirror system which looks out the side of a nadir zenith pointing spacecraft and provides pitch and roll control plus gyroscopic stability in yaw. The overall control system has as magnetic field sensors and/or sun sensors for additional references. It operates autonomously and would provide reference data to the APT for its acquisition function. Figure 4 illustrates a system configuration with two scanwheels.

Such systems have been built by Ithaco, Inc., to provide 3-sigma stability to 0.3 degrees. This was in a unit somewhat more complex than might be incorporated into an XSAT-size spacecraft, but design work on a smaller system is underway. We can expect that our APT XSAT would be stable in zenith reference to 0.5 degrees or so, and design the acquisition system to allow for slow wandering about this pole. The Ithaco system dumps excess wheel momentum and corrects for roll errors by interacting with the earth's field through magnetic torque bars. The details of the system interactions, wheel and torque currents, are too complex to discuss here, but involve moment-to-moment determination within the spacecraft flight computer of the direction and strength of the local earth magnetic field relying on the 3-axis magnetometer.

Telescope Support System

Two approaches must be investigated, the choice being made on the basis of the science adequacy and the momentum management and power management which each would entail. The simplest case would be to body mount the telescope system, as was done with the Hubble Space Telescope and all previous earth-orbiting astronomical observatories. Pointing is achieved by rotation of the entire spacecraft to acquire the program object, and the stabilization involves the entire mass and momentum of the vehicle. This drives the sizing of the momentum wheels, the magnetic torquers, and the response of the system to atmospheric drag and gravity-induced torques. Repointings are kept to a minimum, and the time to repoint is frequently long, both of which favor science which requires long dwell times on individual target fields. The HST can repoint by some 90 degrees in 18 minutes, slower than the hour hand of a clock. Slews to a new target require exercise of the momentum wheels and management system, consuming part of the daily power budget, draining the batteries to a must-charge level. Tasking discipline may not allow science data to be collected on every orbit. The science productivity of this mode must be compared with that possible with a gimbals-mounted system. This would allow the major mass of the spacecraft to remain in a earth-stable configuration; only the telescope and detector would point.

The telescope could be supported within the spacecraft body in gimbals allowing the optic axis to be pitched fore and aft by some 15 degrees and rolled port and starboard by 20 degrees. This would allow access to a 40-degree swath of the celestial sphere on each orbit. The system must incorporate kinematic balancing masses so that gimbals movements do not interact with - and load - the spacecraft momentum wheel. Precession will walk successive orbits westward by some amount, assuming posi-grade orbits, depending on the orbital inclination. The roll limits would allow additional observations of the same object on successive orbits over a period of three to ten days. The fore and aft motion would allow 7.5 minutes for acquisition and subsequent observation of a given star or star field. This might allow 90 to 100 seconds of integration in each of four color bands. The values cited in Genet and Hayes, 1989, p66, computed for a 0.5-meter telescope, must be modified to recognize the smaller aperture which could be configured in a XSAT. As we shall see, it is more reasonable to expect a 0.25-meter aperture equivalent. This could limit the science undertaken to some of the 30,000 stars brighter than 7.5 stellar magnitudes. This will be shown to be a minor restriction in any reasonable lifetime for the small-satellite observatory.

One point to be recognized is that the telescope pointing problem is different in orbit than on the earth in several ways. The main one is that we need not move the telescope to cancel the spacecraft inertial motion; we need only to free the telescope from the spacecraft so that the telescope's inertia will allow it to remain pointed at the star. We need only to cancel the small frictional effects which we cannot design out of the support system - and the cable torques which we have designed into the interface. Smaller effects due to the aberration of light and to parallax from our moving platform are probably too small for special treatment.

Possible Optical Configuration

Figure 5 shows views of a compact optical arrangement which might be packaged to provide a low-earth-orbit observatory. The Paul-Baker optical system is noted for its compactness and well-corrected images in the relatively wide field-of-view (> 1 degree is possible) The corrector mirrors are near-spheres combined with a parabolic primary. Focus at the detector system will have only a slight curvature since Petzval compensation can be obtained by adjustment of the secondary and tertiary mirror radii (Schroeder, 1987). The detectors could be either silicon CCD's or IR array detectors since the all-reflective system will have no color aberrations. The concept relies on passive radiative cooling of the detectors by transfer of heat from the focal plane to a radiator using ammonia heat-pipes, a technique already proven in space and incorporated into both the Wide-Field/Planetary Camera (WF/PC) and Faint Object Spectrograph (FOS) for the Hubble Space Telescope (HST). When the sun is above the plane of the entrance aperture of the telescope, and incident on the radiator, observations would probably be suspended due to both scattered light and loss of cooling efficiency.

Details of the detector configuration are still being worked, but a large CCD array is planned which will incorporate the Boyd in-memory acquisition subsystem. Science planning for selection of observers for the HST will be reviewed to select the smaller filter set to be incorporated in the photometers. We have not yet rejected the possibility of a no-moving-parts scheme like the HST High-Speed Photometer (HSP) built by the Univ of Wisconsin, where an image dissector is used behind multiple filters, but there will be limited room and power. A simple photomultiplier is used ground-based systems, but these devices also use 1-kilovolt power supplies as do image dissectors. Simple aperture photo detectors will require quite complex acquisition and pointing algorithms.

Power Considerations

One of the most confining parameters which is faced by an XSAT payload is the small amount of average power which can be supplied by the surface-mounted solar cells. The very rigid structure required by the LCAS attitude control system, along with its limited torquing capability, make the use of larger deployable arrays undesirable. Only a few watts will be made available to the APT during the night side of the orbit, some 45% of the orbital period and perhaps 80% of the best observing time, depending on the orbital inclination and the relative "season"of the orbit plane to the earth-sun line. Observations must be tailored to the power budget, a problem which is shared with the HST, although higher-efficiency solar arrays have now been built by ESA for HST. One would certainly wish to provide the best possible arrays onto an XSAT, even at an increase in cost, since it would literally be penny-wise and power-for-pound foolish to skimp on capability after the trip into orbit.

More power could be available during the sunlit parts of the orbit, when it does not have to pass through the battery-charging system before use, suffering attendant losses. To provide for high-powerprocedures, a greater-than-typical battery capacity can be provided operating only on several orbits per day. Long slews of the telescope, and subsequent recovery of spacecraft stability should be planned during these periods. The number of different targets to be observed during orbital night will ultimately depend on the final power budget, and perhaps the region of the celestial sphere being scanned in any observing "season".

Power considerations will enter into the division of computational between "payload"computer for the science instrument and sharing the bus computer with the attitude and housekeeping software. This is only one of many design studies which must be made, choosing an acceptable duty cycle for the CPU (a hardened 8086 INTEL type).

We anticipate relying on daily single communication with a low-cost ground station, though science programs which could be undertaken with this limitation must be examined as another issue which requires study before a final configuration could be adopted. This is sufficient for our ground systems but may not have adequate reliability for a space system. The check of navigational success in acquiring and pointing may force more frequent monitoring of the daily target tasking.

Operational Concept

As an observatory orbiting the earth, rather than riding on it, the low-earth-orbit APT can might observe stars on both sides of the earth on a single orbit, comparing data with that collected by several ground APTs within the same time frame, APTs working within the framework being established for a Ground Network of Automatic Telescopes (GNAT). (Crawford, 1989). Within constraints of power profile, orbit-plane intersection with the celestial sphere, target brightnesses, and the solar position, many candidate stars might be selected for observation. The problem of choice, and the selection of the next target object must be made on the basis of some prioritization plus the power or stability cost to re-point to the new object. The problem of scheduling might be approached by en extension of the Automatic Telescope Instruction Set (ATIS) software, in which priority, availability, and past observational history are left to the telescope itself, rather than pre-programming every object, every spacecraft system command, every APT housekeeping function in a suite of planning software on the ground.

This latter approach is the one followed by the HST; it has led to the formation of scientific mission planning group of 200 scientists and computer programmers at the Johns Hopkins University, concerned with the generation of every byte of instrument up-link command to turn-on, to calibrate, to expose, and to store the data, including the identification of guide stars, pointing off-sets, closure of protective shutters to protect the detectors when the telescope field sweeps inadvertently across the earth, etc. The suite of science planning software contains hundreds of thousands or lines of code occupying more than a half-dozen VAX computers.

The HST science commands are the screened within a separate operations control center at the Goddard Space Flight Center, equipped with several more VAX computers, to decide what spacecraft commands must be sent, command by command, interspersed within the scientific commands to point the telescope, redirect the solar arrays while the spacecraft moves, charge or discharge the batteries, keep the telemetry antennas pointed upward at one of the data relay satellites, etc.,etc. The stored-command data are so extensive that 2 to 3 command up-links are needed each day to avoid running out of commands. The approach to be taken with our LEO APT is expected to avoid the need for extensive ground planning, while keeping a reasonable level of operational efficiency (% of orbit time actually being used to collect data. HST will reach 35% after some two years, but will expect only 15-18% initially.

The early definition and launch of a Low-Earth-Orbit APT, following hard on the heels of the Hubble Space Telescope, set for the end of 1989 or early 1990, will provide valuable experience as well as a productive scientific and educational tool leading into the design of larger, long-lived orbiting APTs on the FREEDOM space station.

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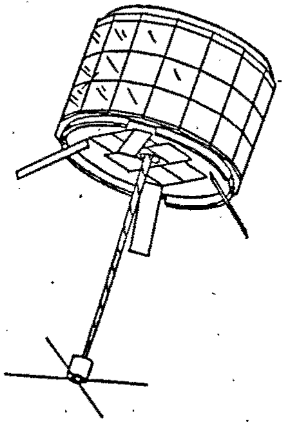

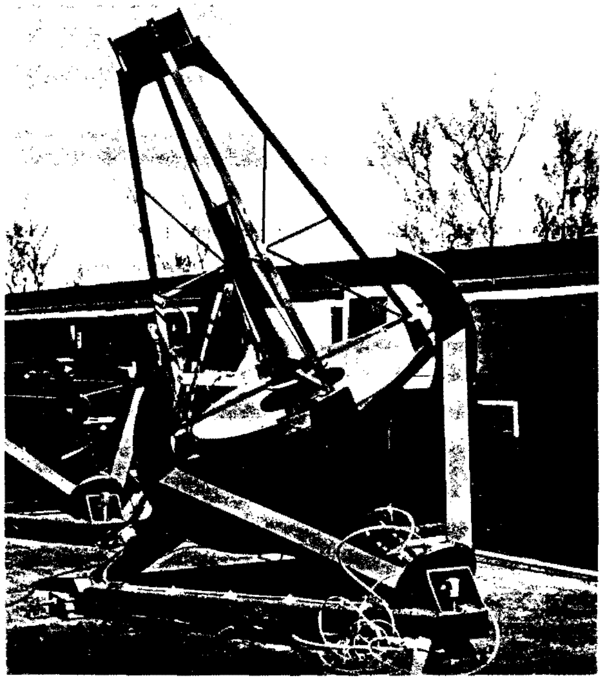

FIGURE 1. Gravity-Gradient Small Satellite, Nadir Stabilized

FIGURE 2. Ground-Based Automatic Telescope of 0.75-meter Aperture

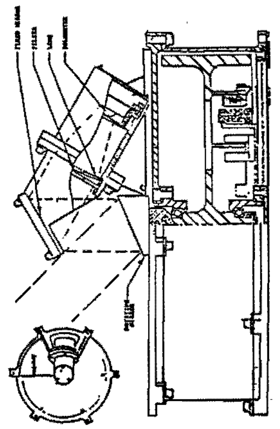

FIGURE 3. Lucas Scanwheel (TM) Concept. Spin axis of rotating wheel coincident with pitch axis, stabilizing spacecraft in both roll and yaw. A mirror scans the bolometer across the carbon-dioxide emission layers of the lower atmosphere.

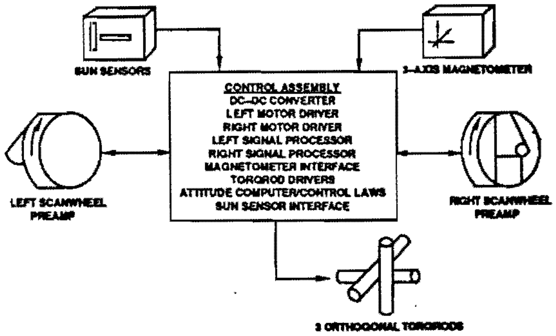

FIGURE 4. Control System Concept for Two-Wheel/Scan Mirror with Magnetic Field Torque Dumping.

FIGURE 5. Possible Optical Arrangement for Low-Earth-Orbit Automatic Telescope.