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HIGH RESOLUTION OBSERVATIONS OF LOW CONTRAST PHENOMENA FROM AN ADVANCED GEOSYNCHRONOUS PLATFORM (AGP)

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1. ABSTRACT

Present technology allows radiometric monitoring of the earth ocean and atmosphere from a geosynchronous platform with good spatial, spectral and temporal resolution. The proposed system could provide a capability for multispectral remote sensing with a 50 m nadir spatial resolution in the visible bands, 250 m in the 4μm band and 1 km in the 11μm thermal infrared band. The diffraction limited telescope has a 1 m aperture, a 10 m focal length (with a shorter focal length in the infrared) and linear and area arrays of detectors. The diffraction limited resolution applies to scenes of any brightness but for a dark low contrast scenes, the good signal-to-noise ratio of the system contribute to the observation capability. The capabilities of the AGP system are assessed for quantitative observations of ocean scenes. Instrument and ground system configuration are presented and projected sensor capabilities are analyzed.

2. INTRODUCTION

An advanced Geosynchronous Platform, called AGP in the rest of this paper, can provide significant new observation capabilities in the Visible and Infrared spectral region for studying the oceans, land and atmosphere (Otterman, 1983). A satellite at an altitude of 35,870 km in an equatorial orbit will move in synchronism with the earths rotation and thus appear to hover over a fixed point at the equator. The primary advantages that result from geostationary observations occur because the earth appears to be stationary under the satellite. The unique capabilities that result are:

- observation, on demand, of approximately one-fourth of the world
- observation of short lived events
- observation of diurnal variations
- high spectral resolution, when desired
- high signal to noise
- interactive data acquisition
- constant off nadir viewing

The primary limitations result from the high altitude required for geostationary observations (35,878 km) and the fact that the satellite can only hover above the equator. Even using a very large sensor with a 1 meter aperture, a realistic AGP can provide only modest spatial resolution and because of diffraction effects the resolution is wavelength dependent, as indicated below:

Spectral Band	Instantaneous Field of View (IFOV)
0.4 to 1.0 μm	50 - 100 Meters
1.0 to 2.4 μm	100 - 200 Meters
3.5 to 4.2 μm	400 Meters
10.5 to 12.5 μm	1,000 Meters

The major advantages an AGP may offer for ocean observations will derive from its capabilities to: observe desired areas on demand with optimized observation intervals (from minutes to days); interactive observation, i.e. the experimenter can modify observations based on the results of prior observations, optimization of spectral band selection; and optimization of dynamic range and signal-to-noise ratio.

2.1 Geometric Observation Considerations

The constant location above the equator will lead to observation with oblique, but constant, view angle (nadir angle). This also leads to an increase in the Instanteous Field of View (IFOV) which corresponds to a reduction in resolution as indicated in the following table.

NADIR ANGLE DEGREES	DISTANCE FROM NADIR KM	± LAT/LONG. DEGREES	INCREASE IN IFOV %
10	930	8	2
30	2,800	25	15
40	3,800	34	30
50	4,800	43	50
60	5,800	52	100

2.2 Microwave Observations

Passive microwave observations are not likely to be very useful for ocean observations from an AGP because of the diffraction limited resolution that can be achieved with real apertures as indicated by the following table:

Wavelength (cm)	Frequency (GHz)	Aperture 4m	15m
		IFOV in km	IFOV in km
21	1.4	2,300	600
5	6	540	145
1.5	20	150	40

Synthesized passive apertures to achieve reasonable resolution will be very difficult to achieve and active microwave sensing, such as with a synthetic aperture radar is exceedingly difficult to do at a range of 36,000 km. Therefore, there will be no further consideration of microwave sensing from an AGP in this paper.

3. SYSTEM CONSIDERATIONS

Present launch vehicles can deliver a very limited payload to geosynchronous orbit. The AGP will reqire a high performance, heavy, three axis stabilized space craft carrying a large earth viewing telescope as its primary sensor. A well designed three mirror system can provide the desired field of view with diffraction limited performance over the spectral range of 500 nm to 13 micrometers.

3.1 Sensor Configuration

The weight of a telescope tends to grow as the cube of the aperture diameter. The diffraction limited performance grows linearly with the aperture. The cost of a large diffraction limited moderate field of view instrument grows very rapidly with aperture. All of these considerations tend to limit the maximum aperture to something on the order of 1.6 meters (Perkin-Elmer, 1975, Itek, 1975). In an effort to keep the probable cost of an AGP for ocean observation to moderate levels this paper will concentrate on a sensor with a 1 meter aperture and selectable focal lengths of 3, 5 and 10 meters depending upon the detectors used and the spatial resolution desired. Figure 1 shows a simplified profile view of the sensor.

SIMPLIFIED PROFILE VIEW

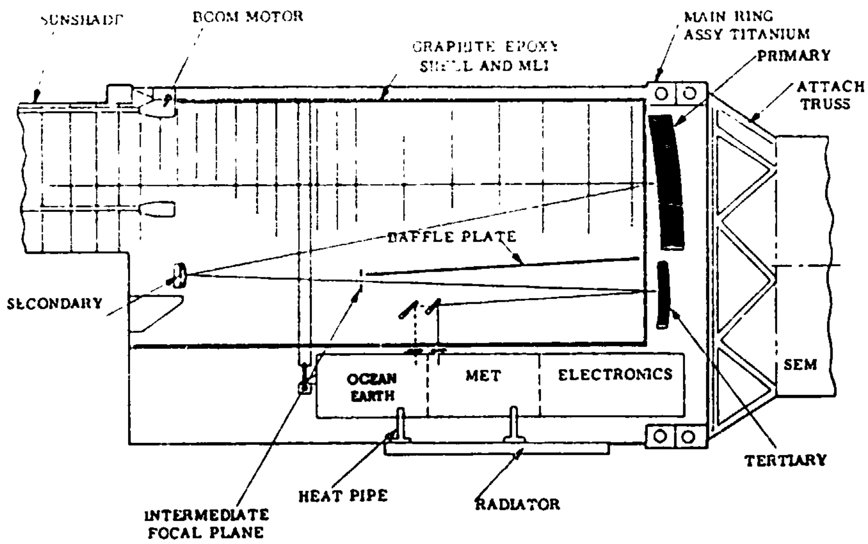

Figure 1

3.2 Diffraction and Modulation Transfer Function Considerations

The sensor design is dominated by diffraction considerations. An imaging radiometer must have a high Modulation Transfer Function (MTF) if it is to produce accurate measurements of the scene radiance. MTF is a measure of the relative response of the system to a sine wave modulated input radiance at various spatial frequencies to that at very low spatial frequencies (almost DC). Figure 2 shows how the diffraction limited MTF varies with the spatial frequency of objects in the sceen in angular units of λ/D per cycle, where λ is the wavelength of the light and D is the diameter of the sensor aperture. The central obscuration is the blockage in the center of some telescope designs. The design proposed for the ACP has zero blockage.

In this paper diffraction limited performance is generally defined to occur when the IFOV = 2.44 λ/D. That corresponds to a diffraction MTF of 0.73 and is shown at a value of 4.88 Angular Units on Figure 2. Figure 3 shows the diffraction limited resolution as a function of wavelength and clear aperture diameter.

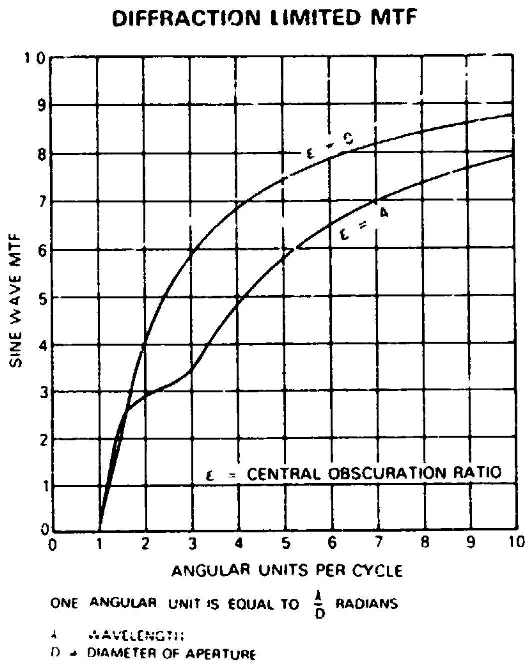

Figure 2

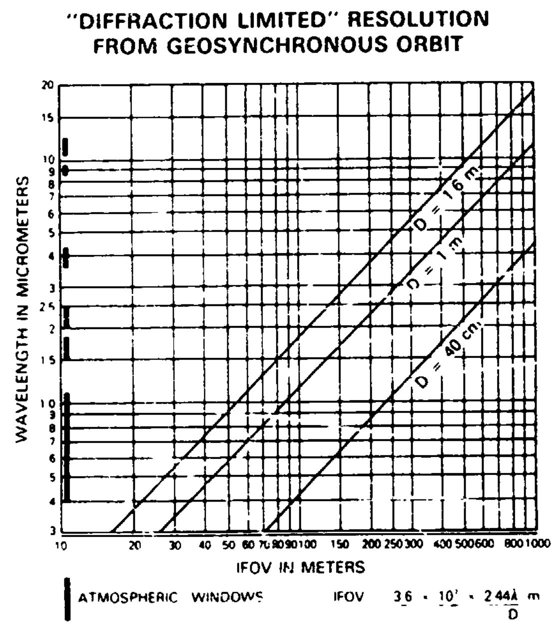

Figure 3

The overall or system MTF is the product of all the elements in the imaging chain and includes the following elements. The value given for each element refers to the response to a signal with 1/2 cycle equal to the IFOV, often referred to as the Nyquist frequency.

Diffraction--0.73
Detector size--0.64
Smear--0.85, due to detector motion during integration time
Diffusion--0.95, due to cross talk in the detectors
Optical Quality--0.9, due to aberations and optical imperfections

The system MTF is the product of all terms and equals 0.33 at the Nyquist frequency. This is a value that will allow radiometric measurements to be made of objects larger than 3 to 4 IFOV's. In orbit the effective MTF is further reduced by the atmospheric adjacency effects in which the atmosphere, especially aerosols, scatter light into the signal path and thus reduce the contrast and in turn the MTF.

3.3 Multispectral Linear Array Approach

The scene radiance in the focal plane of the optics will be selected by dichroic beam splitters and selection mirrors to transfer the desired spectral channel to the appropriate detectors. Reimaging optics will be used to reduce the effective focal length to 3 or 5 meters to optimize the performance in chosen spectral regions or to provide a desired field of view. Silicon linear array detectors which can cover the visible to near IR (VIS/NIR) spectral region from 400 nm to 1,000 nm are in production with dimensions of 15 micrometers or less and with array lengths of from 1,000 to 4,000 detectors. These detectors will provide an IFOV of 50 m in the visible using a 10 meter focal length telescope. Using arrays with multiple lines of detectors on a single chip plus beam splitters will allow the scene to be observed in 12 or more spectral bands in the VIS/NIR region. The number of detectors in the total array will determine the field of view of the system. Total array lengths of from 4,000 to 10,000 detectors are reasonable and will provide a field of view of from 200 km to 500 km. Imaging these arrays thru the 5 m focal length optics would provide an IFOV of 100m and a FOV of from 400 km to 1,000 km. The line of detectors would be arrayed in an east west direction and the spacecraft would scan north and south at the appropriate rate to acquire the full scene. As is discussed in a later section the scan rate will be selected so as to achieve the required signal-to-noise ratio.

Detectors are under development in the Short Wave IR (SWIR) region, between 1 and 2.5 micrometers, with dimensions of 30 micrometers and array lengths of 512 detectors on a chip. These detectors can provide 100 m IFOV using the 10 m focal length telescope and 200 m IFOV using the 5m focal length. Using from 2,000 to 5,000 detectors in a line is reasonable and will provide a FOV which is the same as that provided by the silicon detectors. A variety of detector systems are under development for this spectral region. Paladium Silicide, Indium Antimonide and Mercury-Cadmium-Telluride are all under development. Use of beam splitters and spectral filters on the chips should allow 6 to 10 spectral bands to be obtained in this region.

The 4 micrometer Mid IR (MIR) spectral region can be covered by detectors produced from Platinum Silicide, Indium Antinomide or Mercury-Cadmium-Telluride. Detectors in this spectral region will probably be larger, on the order of 50 micrometers on a side, and can provide a 400 meter IFOV. It should be feasible to divide the 3.5 to 4.5 micrometer region into 2 bands if desired. The FOV could match that of the other bands. The use of this band in daylight is complicated by the fact that the reflected sunlight is similar in intensity to the thermal flux emited by the scene.

The Thermal IR (TIR) spectral region between 8 and 12 micrometers can be covered by Mercury-Cadmium-Telluride detectors and will probably be about 100 micrometers on a side. This will provide an IFOV of 1000 meters with the 3 meter focal length telescope and a FOV similar to the other bands. It should be reasonable to inclue 4 to 6 bands in this region.

The following Table shows FOV, IFOV and Data Rate considerations for the MLA System.

Field of View		Number of Detectors/Band					Data Rate* KB/SEC				
		Spectral Region IFOV (M)					Spectral Region IFOV (M)				
		VIS/NIR	SWIR	SWIR	MIR	TIR	VIS/NIR	SWIR	SWIR	MIR	TIR
KM	Degrees	50	100	200	400	1,000	50	100	200	400	1,000
200	± 0.16	4,000	2,000	1,000	500	200	2,000	500	125	50	4
500	± 0.4	10,000	5,000	2,500	1,250	500	5,000	1,250	312	125	10

* SCAN VELOCITY = 2.5 km/sec and 10 bits/Pixel.

3.4 Alternative Focal Plane Systems

There are other techniques to provide the multispectral sensing required for ocean observations. The preferred approach depends upon the desired spatial resolution, spectral resolution, number of bands, and field of view.

--Imaging Spectrometer

If a large number of moderately high spectral resolution bands are desired, especially in the range from 400 nm to 2.5 micrometers at relatively low spatial resolution, i.e. 200 to 400 meters and modest FOV, i.e. 100km, then an imaging spectrometer may be the preferred approach. Using this technique the VIS/NIR region can be partitioned into 60 bands of 10 nm spectral bands width each and the SWIR region into 60 bands of 20 nm spectral band width each. In this technique the scene is first imaged on a slit. The image passing through the slit is collimated, dispersed by a prism or a grating, and then reimaged onto rectangular arrays of detectors in which one dimension of the array is spatial and the other is spectral. The required reimaging and spectal dispersing systems are large and heavy and thus will be limited to applications with moderate spatial resolution requirements.

--Area Arrays

If very high spectral resolution is desired, i.e. less than 10 nanometers, but a moderate number of spectral bands are desired, a simpler technique is available. The scene is imaged onto an area array of detectors through a spectral defining filter mounted on a filter wheel selection device. This approach provides good geometry to determine the relative position of objects and thus simplifies determining relative motions of clouds and water. Its major virtue is that since an entire scene is imaged at one time very long integration times can be used which allows the use of correspondingly narrow spectral intervals. Silicon arrays covering the VIS/NIR region are presently available with 256 x 256 detectors on 30 micrometer centers, and it is reasonable to project that arrays of 1024 by 1024 detectors will be available in the near future. It is reasonable to project the development of arrays of 256 x 256 in the SWIR band and 128 x 128 in the 4 micrometer band.

The following table gives a feel for the IFOV's, FOV's and data rates that such area arrays could provide in the AGP sensor.

Spectral Region (m)	Array Size	Detector Size (m)	Focal Length (m)	IFOV (m)	FOV (km)	Data Rate MB/S
.4 - 1.0	1024 x 1024	30	10	100	100	21
			5	200	200	21
			3	360	370	21
.4 - 1.0	512 x 512	30	10	100	50	5.2
			5	200	100	5.2
			3	360	185	5.2
1.0 - 2.5	256 x 256	50	5	350	90	1.3
			3	580	140	1.3
3.5 - 4.2	128 x 128	50	5	350	45	.3
			3	580	75	.3

*AT 10 BITS/PIXEL, READOUT PERIOD OF 500 ms

3.5 Signal-to-Noise Ratio Considerations

An AGP can provide an excellent signal-to-noise ratio in narrow spectral bands over a wide range of illumination conditions. This can be done by controlling the time a detector look at a given area (IFOV) so as to build up an adequate signal level which is then digitized and sent to the ground. In the VIS/NIR and SWIR bands the detectors can be considered photon counting devices (with the appropriate quantum efficiency) and the preamplifier and dark current noises are small, typically under 100 electrons. The dominent noise component for signal-to-noise values greater than 100 to 1 is the shot noise or random fluctuation of the signal flux during the integration time which varies as the square root of the number of signal electrons.

There is a maximum number of signal electrons that can be measured at any pixel in a scene for a given detector system before the data saturates or becomes too nonlinear to calibrate. Linear arrays often have a maximum capacity of about 200,000 electrons and a noise level in the order of 100 electrons. Area arrays often have a maximum of 300,000 electrons and a noise level of 200 to 300 electrons, or more.

The analog-to-digital converter is another source of noise in the system. The quantizing noise is equal to the quantizing step size divided by the square root of 12. The quantizing step size is equal to the full scale signal divided by 2 to the nth power, where n is the number of bits in the analog-to-digital converter. Another, harder to quantify, source of noise is due to calibration errors and is discussed in another section. The noise contributors combine as the square root of the sum of the square of the noise sources.

The following table gives some typical values for the systems.

Se Number of Signal Electrons	Signal to Noise Ratio: Number of Noise Electrons (Ne) 100	200	300	500	Quantizing Noise (Electrons), Full Scale = Se: Number of Bits in A D 8	10	12
500,000	700	680	650	580	560	140	35
300,000	550	530	500	420	340	85	21
100,000	300	270	230	170	110	28	7
50,000	200	170	130	90	56	14	4
30,000	150	120	100	60	34	9	2
10,000	70	45	30	20	11	3	-
5,000	40	24	16	10	5	2	-
3,000	27	15	10	6	3	1	-
1,000	9	4	3	2	-	-	-

The Number of Signal Electrons (Se) can be estimated using the following relationships:

$$Se = \left(\left(\frac{S}{\pi}\cdot Ta\cdot \mathrm{Cos}Z + Na\right)\cdot R\cdot Tas + Np\right)\frac{\pi\cdot To}{4(f\#)^2}Fb\cdot Tf\cdot Qd\cdot Ad\cdot It \qquad (1)$$

$$Ns = \left(\frac{S}{\pi}\cdot Ta\cdot \mathrm{Cos}Z + Na\right)\cdot R\cdot Tas \qquad (2)$$

All of the variables may vary with the wavelength, λ, of the radiation with the exception of the solar zenith angle.

- S Solar irradiance in number of photons/sec/cm^2/nm at top of atmosphere
- Ta Transmission of the atmosphere to the surface
- Z Zenith angle of sun
- Na Atmospheric radiance, number of photons/sec/cm^2/sr/nm scattered onto the surface from the atmosphere
- R Reflectivity of target
- Tas Transmission through the atmosphere from the surface to the sensor
- Np Radiance added by the atmosphere to the signal in photons/sec/cm^2/sr/nm
- To Transmission of the optics
- f# f number of optics = focal length/aperture
- Fb Bandwith in nm of spectral defining filter
- Tf Transmission of the spectral filter
- Qd Quantum efficiency of the detector
- Ad area of the detector in cm^2
- It Integration time in seconds
- Ns Surface radiance in photons/sec/cm^2/sr/nm above the atmosphere

There is a complex interrelationship between many of the atmospheric terms, especially the atmospheric path radiance, which is a function of wavelength, sun angle, angle to sensor, target and surround reflectivity, and the state of the atmosphere.

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The following table gives representative value for some of these parameters.

Sample calculation of Signal-to-Noise Ratio (S/N) and Noise Equivilent Delta Reflectivity (NEDR)

λ μm	S x10[13]	Ta	Z	Na x10[13]	R	Tas	Ns x10[13]	Np x10[13]	f#	Fb	Qd	Ad x10[-6]	It x10[-3]	Se x10[3]	S/N	NEDR %
.45	44	.7	30	3	.1	.7	.8	3	10	20	.7	2.2	40	110	315	.15
.45	44	.6	60	2.5	.1	.7	.47	3	10	20	.7	2.2	40	100	301	.25
.55	47	.8	30	2	.05	.8	.49	2	10	20	.8	2.2	40	80	265	.1
.55	47	.6	70	1.5	.05	.8	.18	2	10	20	.8	2.2	40	75	260	.2
.65	50	.8	30	1.	.05	.8	.48	1.	10	20	.8	2.2	40	50	205	.08
.65	50	.8	30	1.	5	.8	4.8	1.	10	20	.8	2.2	40	100	425	.14
.75	47	.9	60	.7	.05	.9	.34	.5	10	20	.8	2.2	40	30	150	.08
.85	41	.9	60	.5	.05	.9	.29	.3	5	20	.5	2.2	80	90	285	.04
1.2	28	1	30	.2	.2	1	1.6	.2	10	20	.2	9	80	120	335	.07
1.6	19	1	30	.1	.2	1	1.1	.1	10	40	.15	9	80	120	335	.07
2.2	9	1	30	0	.2	1	.50	0	5	40	.05	9	160	135	355	.06

Note, To = 0.5, Tf = 0.6 for all λ for these calculation
100 noise electrons assumed for S/N calculation

It should be noted that for a given set of scene conditions the items that can be selected to provide the needed signal to noise ratio are primarily the optics f number, detector size, spectral bandwidth and integration time. The geostationary orbit is unique in that it allows adjustment of the integration time to allow the required signal-to-noise to be obtained. In a low altitude orbiting satellite the integration time must be less than the dwell time (IFOV/velocity) and for a system with an IFOV of 50 m and a sub-point velocity of 7km/sec the maximum integration time is 7 milliseconds. In geostationary orbit the integration time is fundamentally limited by the stability of the spacecraft and the maximum signal that the detector can accommodate. The need to cover a given area in the observation time allowed is also an operational limitation.

The Noise Equivelent Delta Reflectivity (NEDR) is that change in reflectance which produces a change in the signal level just equal to the RMS noise of the system. A large object (say 6 x 6 IFOV's) with a change in reflectivity equal to the NEDR would be detectable, but the precise locations of its boundary would be hard to determine because the peak-to-peak noise is about 6 times the RMS noise. To reliably observe a small object (say 2 x 2 IFOV's) would require an NEDR 4 to 6 times smaller than the reflectivity difference between the object and the background. The relationship between Signal/Noise and NEDR is given by the following formulas using the notation from the previous table.

$$\mathrm{NEDR} = \frac{R(Ns + Np)}{Ns \cdot S/N}, \quad S/N = \frac{R(Ns + Np)}{Ns \cdot \mathrm{NEDR}} \qquad (3)$$

Note that in the absence of any path radiance the Noise Equivelent Delta Reflectivity equals the reflectivity divided by the signal-to-noise ratio.

3.6 Calibration Considerations

Calibration of the detectors may limit the ultimate signal to noise ratio that can be achieved in the AGP system. A system that uses many detectors in each spectral band exhibits stripes or banding in images due to imperfect calibration. A sensing system that uses only one detector per spectral band can have calibration errors that lead to radiometric errors in the data but all of the data in a given band will be uniformly in error at any radiance level. In a system with many detectors in a given band, calibration errors lead to pixel to pixel variations in output even if the input radiances are identical For many applications of the AGP very good signal to noise performance is required, often in excess of several hundred to one. As is indicated in the section on Signal-to-Noise Ratio, achieving such performance is feasible with the AGP because of the freedom to select the integration time however calibration errors may provide the ultimate limit.

Preflight calibration is essential to provide information on the spectral bandpass of the detectors and their absolute radiometric sensitivity. Variations with time and launch induced effects must be measured while the instrument is in orbit. Many approaches to inflight calibration are available, but there are no techniques that are fully satisfactory in providing the very precise detector to detector calibration required to destripe the data and to provide the band to band calibration or absolute calibration required for interpretation of the data.

One of the best calibration techniques is to fill the aperture with difuse radiation of known intensity. This can be done by deploying a difuse reflector in front of the telescope and reflecting sunlight from it into the sensor. The primary problem with this technique is related to the problem of knowing how the reflectance characteristics change with time. There now exist "Absolute Detectors" whose calibration should be stable with time to measure the input radiance, but it is difficult to apportion that among the spectral bands. There are also engineering difficulties in reliably putting a reflector in front of 1 meter aperture. The AGP may use such a calibration scheme, but it would be used only occasionally, perhaps every few weeks and the reflector would be enclosed at all other times to minimize its reflectivity changes during the life of the mission.

The moon offers the possibility of a good transfer calibration standard. It will be possible to observe a fully illuminated moon every month and it seems reasonable to assume that the moons' reflectivity changes only very slowly with time so that changes observed during the mission can be attributed to sensor changes.

The short term detector to detector calibration will require internal calibration systems using lamps or mirrors to inject a controlled radiance onto the detectors. The fundamental problem in all of these approaches is to assure the uniformity, or knowledge of the variation, of the detector irradiance to one part in a few hundred and to be able to vary the irradiance levels and know their values to a fraction of a percent.

4. APPLICATION CONSIDERATIONS

4.1 Ocean Color

Many ocean parameters can be acquired by observation of the surface color and its change with time. The AGP can acquire data on the ocean color in the spectral regions from 400 nm to 1,000 nm with spatial resolution of 50 to 100 meters, spectral resolution of 20 nm or less and with a signal to noise of better than several hundred to one. Observation of diurnal and tidal changes will be easy from the AGP. Such observations can provide information on water pollution, upwellings and ocean nutrients. Sun glint can be either a problem or a source of information of surface roughness from which surface winds can be deduced.

4.2 Ocean Temperature

The AGP can provide ocean temperature data with a Noise Equivalent Delta Temperature of less than 0.5 degrees Celcius with some capability of correction for atmosphere effects by using two or more bands in the 10 to 12 micron region and by use of the 4 micron band at night. The ability to observe on demand will increase the probability of getting data when the atmosphere is clear. The constant view angles will make change detection easier, but the large view angles may limit data usefulness at distances greater than 4,000 km from the nadir location of the AGP.

4.3 Atmospheric Interactions

The good spatial, spectral, and temporal resolution of the AGP combined with its high signal to noise will offer a unique capability to observe the dynamics and diurnal interaction of the ocean and atmosphere. Selected test areas can be observed hourly for many days coincident with ship and aircraft observations and used to extend these observations to a much larger area. The real time nature of the observation will allow using the AGP data to direct surface and air observers to regions of maximum interest.

The AGP will allow the detection of small clouds as they are being formed and to observe how they change and move to provide information on atmospheric wind fields and other important parameters. Low level clouds are sensitive to heat, moisture and other energy interchanges between the ocean surface and the atmosphere. There is the possibility of learning more about these interactions by detailed observations of these clouds. Thin small clouds are difficult to detect because they present a small reflectance change against a dark ocean background. The ability to optimize the integration time to build up the signal will allow the AGP to provide the necessary performance even when the sun is within 20 degrees of the local horizon.

5. GROUND SYSTEM

The AGP system will consist of tahe satellite, a central ground command, control and preprocessing system and the experimenters or users of the data at locations convenient to their facilities or experimental test sites. These user facilities will interconnect to a central site via telephone lines or satellite communications as appropriate. A communication link of between 50 kb/s and a few million bits per second will suffice for transmitting the data to almost all experimenters. A possible scenario of the operations follows. Low resolution images of all of the current test sites would be distributed to the appropriate experimenters every few hours. Short range meteorological forecasts would also be distributed to aid in the experimenters scheduling their data requests. These acquisition requests would be sent to the central facility by a computer-to-computer link.

The control center would establish the planned observation sequence for the next few hours, inform the experimenters of the schedule and control the spacecraft so as to acquire the data. The data would be received at the central facility, calibrated, geometrically located, and the desired data sent to the requesting investigators. All data would be archived in a form to allow recalibration without loss of any data quality. In most cases the processing and data distribution would be done in near real time so that the data would be available to the experimenter within a few minutes of acquisition. It would be routine for an experimenter to request a minor modification of the operation plans, such as spectral band selection, integration time adjustment, etc. as a result of one observation in time to affect his next observation. Some experiments that require large area coverage of high resolution data will not be able to receive the data over a moderate bandwidth link. In these cases the experiment plan can call for distributing subsampled or averaged data in near real time and sending the full resolution data at a slow rate or via mail. There will also be capabilities to support guest investigators at the central facility who will be able to use the more powerful computing and display systems that could be located there.

6. REFERENCES

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