THE DEVELOPMENT OF A LOW COST EARTH SENSOR

Richard H. Anderson
Lockheed Missiles & Space Company, Inc., Sunnyvale, CA

ABSTRACT

A Low Cost Earth Sensor (LCES) is under development at Lockheed Missiles & Space Company (LMSC) that will be adaptable to both Geosynchronous (GEO) and Low Earth Orbit (LEO) applications. The LCES is based on the latest pyroelectric detector array technology. It has been designed with a minimum of components, using ASIC and hybrid electronics techniques. The sensor will be contained in a single package with a weight of less than 2.5 pounds and a power requirement of less than 2.0 watts. It can be designed to be fully redundant. There are both low accuracy (± 0.5 deg) and high accuracy (± 0.03 deg) versions. For GEO applications, the Earth is imaged onto an X-shaped focal plane, with the horizons at the mid-points of the arms. Pitch and Roll can be calculated from this horizon location information. For LEO applications, a reflective pyramid is added to the front of the aperture to project the images of the horizon at four locations to the same focal plane positions. The design will be presented along with the results of development testing.

INTRODUCTION

This paper is written to describe a proposed Low Cost Earth Sensor (LCES) for use in both geosynchronous (GEO) and low Earth (LEO) orbit applications and present the results of the 1991/92 ID Programs funded to develop the concept. This sensor uses the latest technology in pyroelectric detector arrays and packaging techniques to provide excellent performance in a low cost, light weight package. For the purposes of this paper all discussions will be relevant to both sensor types. If the discussion is unique to only one of the sensors, the title will be followed by a GEO for geosynchronous operation and a LEO for low altitude operation. The analyses presented are to demonstrate feasibility of the design, not represent a hard design. The development program for 1991 involved testing two types of pyroelectric detector arrays, performing some worst case computer analyses, designing the opto-mechanical front end, and reporting the results. For 1992, a full 40 element focal plane has been purchased, new optics designed, the packaging refined, and a development unit fabricated for testing. The test results are not available at the time of this publication, but will be available as an addendum upon request from the author at 2 Sandstone, Portola Valley, CA 94028.

OPERATION

BASIC PRINCIPLES

The basic sensor uses four 9-element pyroelectric detector arrays (there are other configurations which will be discussed later), sized, with the optics, to cover about 1 deg per element. The Earth's horizons, at four locations 90 deg apart, are imaged onto the detectors (Figure 1). For LEO applications a pyramid is used to reflect the horizons to the focal plane. Since pyroelectric detectors require AC signals, a chopper is provided at the

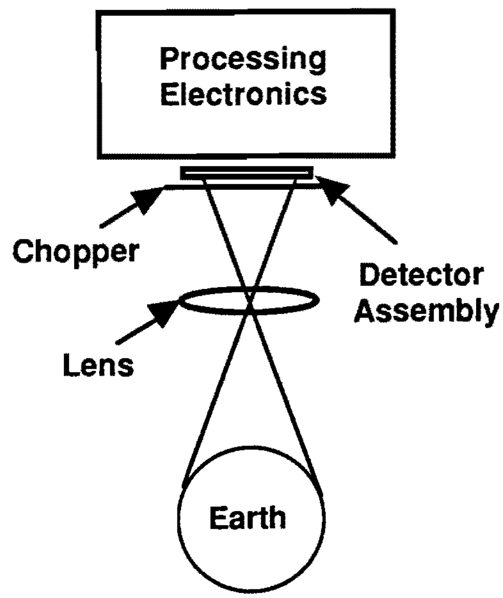

Figure 1-GEO, Geosynchronous Operation

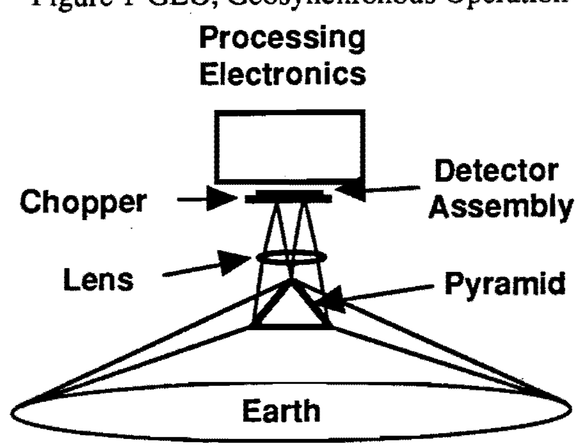

Figure 1-LEO, Low Altitude Operation

focal plane. The detector signals, proportional to the amount of Earth imaged on them, are sampled with a multiplexer and converted to digital values. With this information, the digital processor calculates a horizon location for each of the four detector arrays.

SIGNAL FORMATION

For the GEO applications the Earth is imaged at the focal plane with the horizons at the center of the arrays (Figure 2GEO). There are an additional four detectors used for acquisition. For the LEO applications each face of the four sided pyramid uses 1/4 of the aperture and relays a horizon signal to a corresponding detector array. The angles of the pyramid faces are nominally set for the planned altitude to direct the horizons to the centers of the arrays (Figure 2LEO). The acquisition detectors are not used. In either case, the detectors closest to the optical axis will receive full Earth radiation and those furthest from the optical axis will receive full space radiation. Since pyroelectric detectors respond only to changes in radiation, a synchronous, 8 Hz chopper is used just before the focal plane. Each detector signal is proportional to the difference between the Earth's radiation and the chopper radiation. A masked, 14.1-15.8 μm filter is used as a window for the focal plane assembly to minimize stray light and Earth radiance variations.

SIGNAL PROCESSING

A block diagram of the sensor is shown in Figure 3. The 8 Hz signals from the detectors are amplified then synchronously demodulated with a clock signal from the chopper circuits. Each detector signal is then compared to the space reference for its array at the input of a differential amplifier. The outputs of these amplifiers are then multiplexed through an 8-bit A/D converter to the digital logic. The signals are first normalized for the local radiance conditions by using the Earth reference detectors of each array to set the full scale value for the A/D converter. Then, checking from the space end of the array, the detector to first exceed a threshold of 20% is located and its signal used to make the position calculation. The horizon position is defined to be at a location proportional to the level of that signal. For the low accuracy version of the LCES (Figure 4), the detector signals are input to a comparitor and then, through a buffer, sent directly to an output register. This provides information to the nearest degree at the array and to about 0.5 degree, 3 sigma, after pitch and roll calculations.

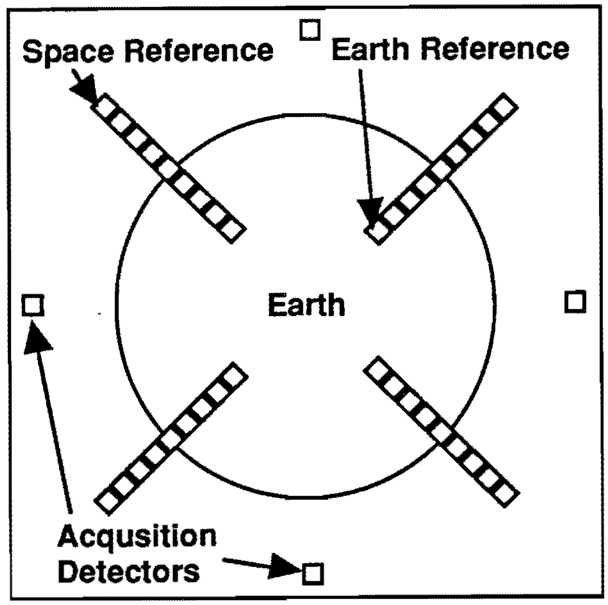

Figure 2GEO, Direct Image

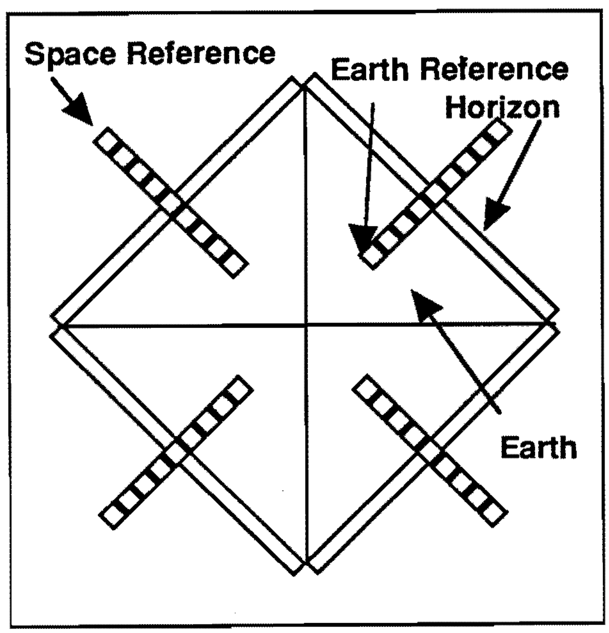

Figure 2LEO, Reflected Images

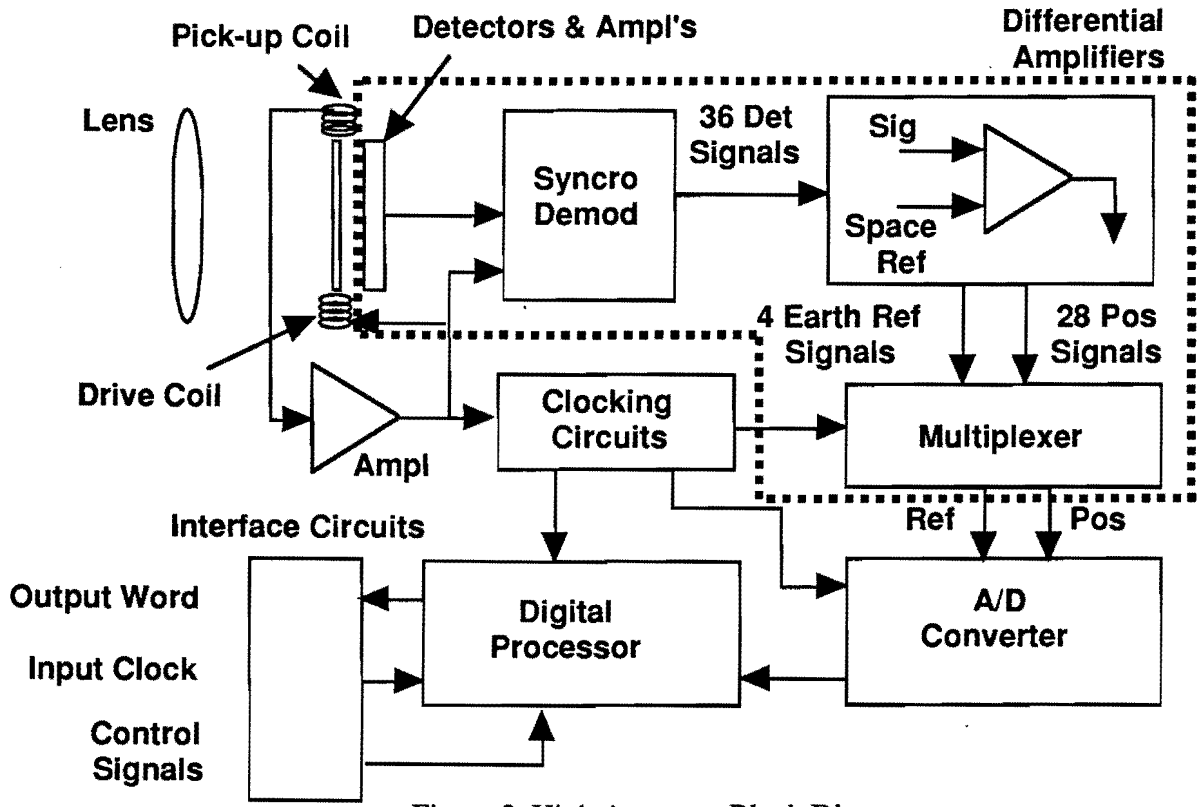

Figure 3, High Accuracy Block Diagram

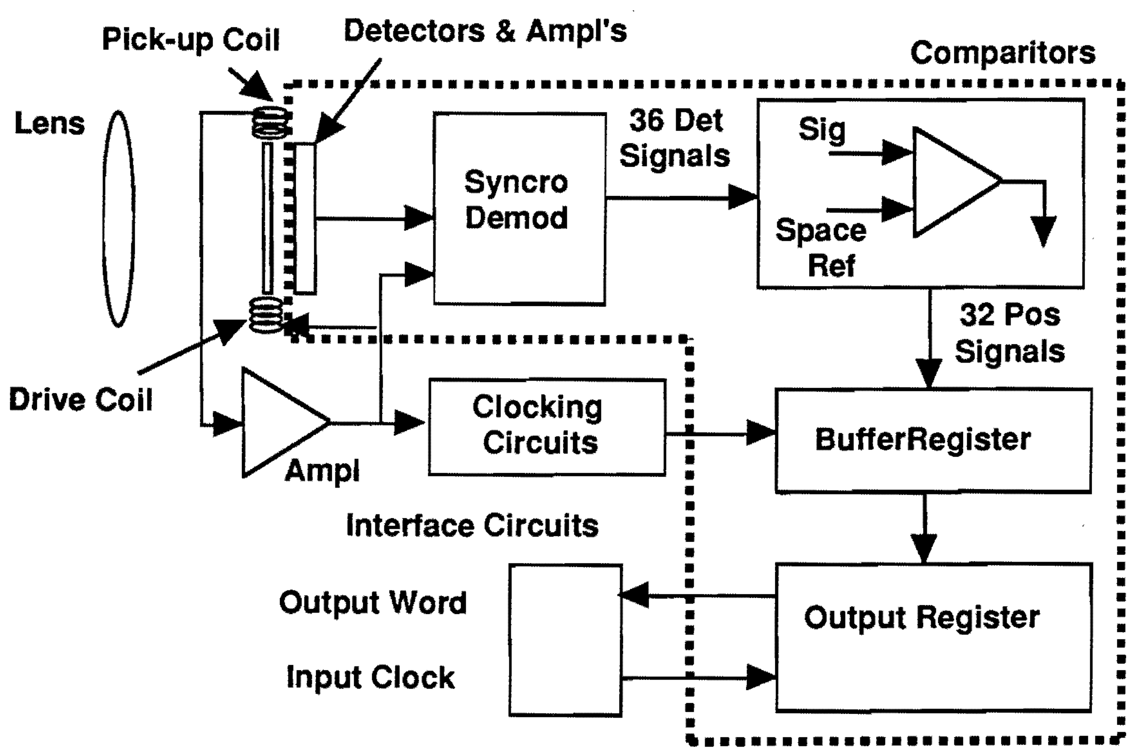

Figure 4, Low Accuracy Block Diagram

For acquisition, the space reference detector in each array and the four labeled acquisition detectors are sent to comparitors in opposing pairs. This information is then sent to the output register. This will allow location of the Earth up to 21° off the optical axis from GEO.

ATTITUDE DETERMINATION

The attitude determination calculations are made in the spacecraft computer with the horizon position information from each detector array. The detector arrays are oriented at 45° to the spacecraft pitch and roll axes. This minimizes seasonal Earth radiation errors and makes three array operation simpler. With the nomenclature as shown in Figure 5, the following equations describe the attitude calculations. A, B, C, and D are the horizon position values of the four arrays.

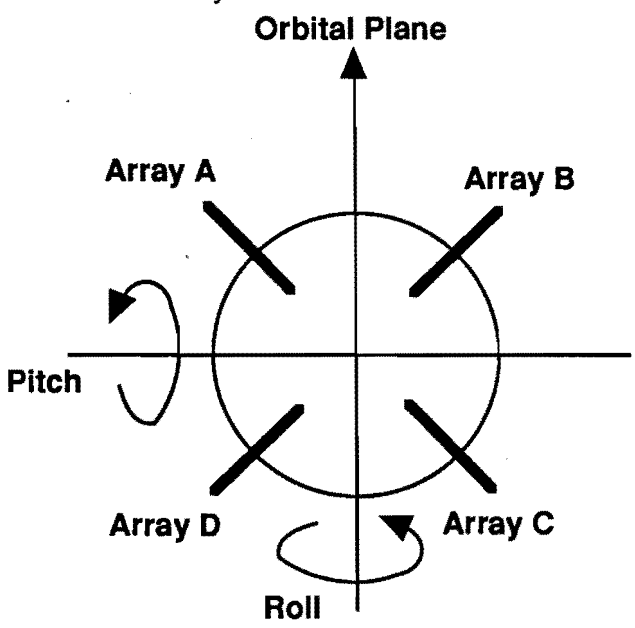

Figure 5, Attitude Determination Nomenclature

For four array operation

Pitch: $P = 0.707(A+B-C-D)/4$

Roll: $R = 0.707(A-B-C+D)/4$

For three array operation

In this mode, altitude effects must be determined. If X is the displacement along the detector arrays at zero attitude for the altitude of the orbit, and Y_N the actual displacement of the horizon at detector N due to an attitude change, then

$A = X+Y_A$, $B = X+Y_B$, $C = X+Y_C$, and $D = X+Y_D$

To determine X, set P and R at zero, then A, B, C, or D = X. To minimize alignment errors, compute

$X = (A+B+C+D)/4$

It can also be computed from

$X = (A+C)/2$ or $X = (B+D)/2$

and, Y_N is determined by

$Y_A = Y_C = (A-C)/2$ and $Y_B = Y_D = (B-D)/2$,

Therefore, if one array cannot be used

$P = 0.707(Y_A+Y_B) = -0.707(Y_C+Y_D) = 0.707(Y_A-Y_D) = 0.707(Y_B-Y_C) = 0.707(A+B-2X) = 0.707(C+D-2X) = 0.707(A-D) = 0.707(B-C)$

and

$R = 0.707(Y_A+Y_D) = -0.707(Y_B+Y_C) = 0.707(Y_A-Y_B) = 0.707(Y_D-Y_C) = 0.707(A+D-2X) = -0.707(B+C-2X) = 0.707(A-B) = 0.707(D-C)$

SUN INTERFERENCE

Since the spacecraft attitude can be determined with data from only three arrays, if the sun is in any one of the four, attitude information is still available. The presence of the sun can be determined three ways: from spacecraft ephemeris information; from sun sensors attached to the Earth sensor; or, with some decreased accuracy, from logic applied to the signal levels from the individual detectors.

ALTERNATE DETECTOR CONFIGURATIONS

The standard detector configuration, as shown in Figure 2, produces a sligthly non-linear output as the horizon moves along the array.

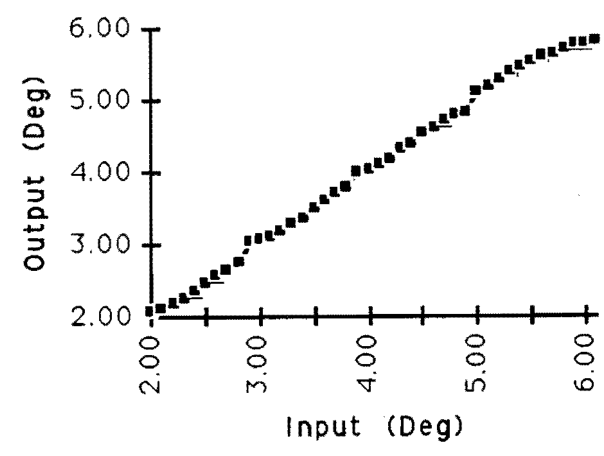

Figure 6, Single Array Linearity

This is due to the necessary spacing between detectors. The effect is illustrated in the data shown in Figure 6.

The actual affect on the Pitch and Roll linearity is yet to be determined, but should be much less than that shown for a single array.

To minimize the above effect, it is possible to have two arrays, offset by half a detector, as illustrated in Figure 7. The linear, center half of each detector is then used for position information.

Super Linear Output

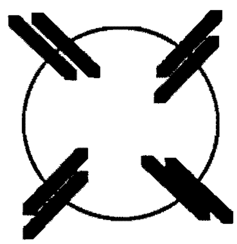

Figure 7, Linear Configuration

Along this same theme, a totally redundant sensor could be made by configuring the arrays as shown in Figure 8 and providing redundant electronics from the multiplexor on.

Redundant

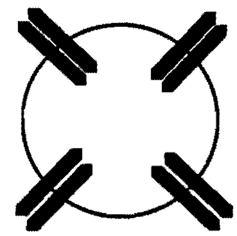

Figure 8, Redundant Focal Plane

To provide extended off-axis performance in Pitch, from GEO, the detectors can be arranged as shown in Figure 9, and the attitude calculations made in a more direct manner. Pitch is the movement along the array and Roll is determined by differencing the chord lengths. The third row can be used for extra high altitude applications or to provide greater range in Roll.

Off-Axis

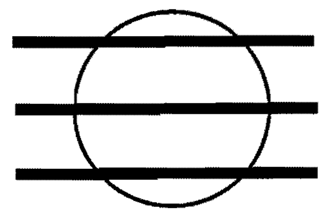

Figure 9, Off-Axis Configuration

SPECIFICATIONS

	GEO	LEO
Size:	4.0 x 4.5 x 3.5 inches	4.0 x 4.5 x 5.3 inches
Weight:	2.3 pounds	2.5 pounds
Power:	2.0 Watts	2.0 Watts
Range: Attitude:	± 2 degrees	± 2 degrees
Altitude:	± 5000 nmi	±100 nmi
Instrument Accuracy:	± 0.02 degrees	± 0.03 degrees
Radiance/cloud Errors:	0.0074 degrees max.	0.0127degrees max.
Noise Equivalent Angle:	0.0014 degrees rms	0.0055 degrees rms
Output Format:	53 bit serial digital word	49 bit serial digital word
Least Significant Bit	0.0039 degrees	0.005 degrees
Operating Temperature:	-20 to +60 °C	-20 to +60 °C

DESCRIPTION

CONFIGURATION

The sensor, including all electronics, will be contained in a single package. The configuration of that package is illustrated in phantom in Figure 10. Shown is the LEO version; the GEO version would not have the pyramid or its support, but would have a removable alignment cube. The focal plane assembly, including the chopper, will be part of the electronics box. The optical barrel, containing the 2-element lens, will be mounted in the electronics box and focussed on the detectors. The pyramid, with its integral alignment mirror will then be mounted to the optical barrel.. This configuration should minimize the assembly and test time. All labsetting and subassembly testing can be performed on the electronics box prior to installation of the optics. All that is required when the optics are installed is alignment testing. The mounting feet have the same pattern as the current Lockheed Earth sensors.

PYRAMID

The 4-sided pyramid, used to reflect the horizons into the lens in the LEO configuration, will have its angles tailored to the specific altitude of interest. The width of the base will be slightly larger then the diameter of the lens to assure maximum radiation transfer. An integral part of the pyramid will be the alignment cube. This unit will be diamond turned out of a single piece of aluminum and coated for maximum reflection and protection. The design approach assures that the alignment mirror tracks the sensor optical axis. For the GEO configuation the pyramid assembly is replaced by an alignment cube which attaches to the box directly.

LENS

The lens will be a 2-element F/1.0 germanium aspheric design developed for a flat focal plane and excellent performance at the required 13 degrees off-axis. It will be sized to 34.4 mm to meet the requirements of this design. The lens is coated with 15 μm anti-reflection coating.

FOCAL PLANE

In developing the LCES we investigated both lithium tantalate and polymer film pyroelectric infrared detector arrays. The polymer film uses a specially processed and prepared PVdF polymer film as the detection element coupled to an integral hybridized high gain, low noise current mode amplifier. These detector arrays are manufactured by Servo Corporation and have been designed for use in the rugged environment of smart munitions.
Servo has pioneered the application of this pyroelectric material to single element devices and now uses its superior properties in a standard linear array. The technical advantages of this material are its large pyroelectric current output in the very thin films used.

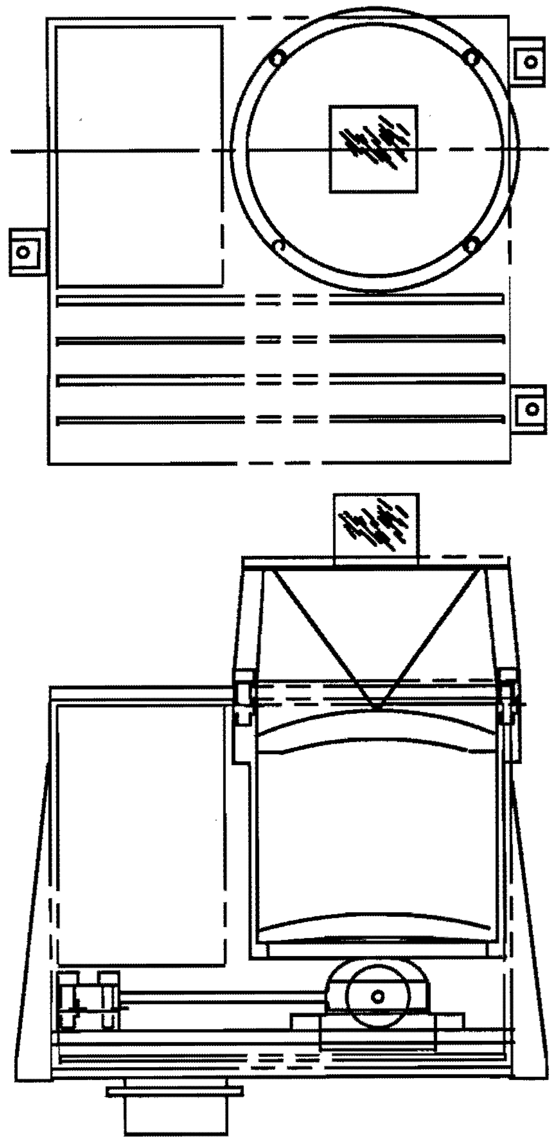

Figure 10, LCES Configuration

This produces arrays with high sensitivity and minimal thermal crosstalk. Since they are produced using photo lithographic techniques, very good spatial registration is obtainable.

The lithium tantalate detectors are single crystal devices, mounted in the appropriate array format. They have greater signal-to-noise characteristics and can withstand higher temperatures than the polymer detectors. They also have integral amplifiers.

For either device, the integral hybridized preamplifier produces an output voltage proportional to the current produced in the pyroelectric element. The current-voltage gain of the amplifier is quite large. However, since it is hermetically sealed in a metal package with the detector, problems associated with using this type of electronic circuit are minimized.

The focal plane assembly will be packaged with four 9-element arrays and four acquisition detectors arranged as illustrated in Figure 2. The window will be a 14.1 - 15.8 µm CO_2 absorption band filter, masked to allow the arrays to operate in an F/1.0 optical system.

In either case, each detector is 0.5 x 0.5 mm with a 0.1 mm gap between elements. The nominal responsivity for the polymer film detectors is 4000 Volts/Watt and the NEP is 1.2×10^{-9} Watts/Hz$^{1/2}$. For the Lithium tantalate, the responsivity is 5000 Volts/Watt and and the NEP is 8×10^{-10} Watts/Hz$^{1/2}$.

The testing program, discussed later, essentially verified these numbers. We have decided to use the lithium tantalate because of its better performance and higher thermal capability. Servo has been able to locate them spatially to the accuracies required for the sensor.

CHOPPER

The focal plane chopper is an important part of the signal formation system. Since the signal on the detectors will be proportional to the difference between the chopper radiation and the radiation from Earth and space, it is important to keep its temperature uniform. When, in the signal processing, the detector signals are normalized to the difference between the space viewing and Earth viewing detectors, the chopper ambient temperature will be normalized out. However, thermal gradients on the chopper could be a source of error. Since the chopper is only used to create an AC signal and does not affect pointing, its motion does not have to be very accurate and slight perturbations will not affect the sensors performance.

The chopper uses the same resonant operating technique as the current LMSC scanning Earth sensors. Its configuration is shown in Figure 11. It is made from a single piece of beryllium copper, used for its excellent thermal and spring properties. The chopper is driven by a pair of magnet/coil combinations. One coil is a pick-up coil which senses chopper motion and sends that signal to an amplifier (Figure 3). The amplifier output signal is applied to the drive coil and moves the chopper at the 8 Hz resonant frequency of the spring/mass system. The chopper amplitude is controlled by sensing the pick-up coil amplitude and controlling the amplifier to the proper gain. The amplitude will be about 0.12 inches, peak-to-peak.

ELECTRONICS

For the following discussions, refer to the Block Diagram in Figure 3.

CHOPPER

The chopper electronics consist of the two coils, the comparitor, and its associated amplitude control circuitry. A load resistor between the reference voltage and the drive coil, is used to control chopper amplitude.

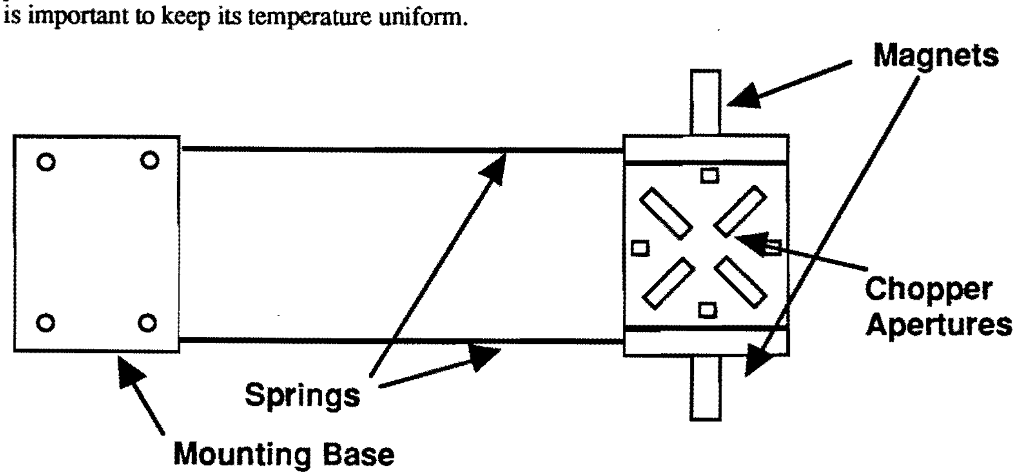

Figure 11, Chopper Configuration

DETECTOR ASSEMBLY

The detector electronics will consist of the hybridized preamplifiers, synchronous demodulators, differential amplifiers to reference the signals to the end, space viewing, detector for each array of 9 detectors, and a multiplexer to provide a serial output signal. These circuits will all be contained within the detector package to minimize the interface connections with the rest of the sensor. The signal due to the difference in chopper temperature and space (calculated below) will be about 0.7 volts out of the preamps. A gain of 5 will be used to operate the synchronous demodulator voltages at a nominal 3.5 Volts. The difference signal into the differential amplifier will then be 50 mVolts. The differential amplifier will have a gain of 50 to provide a maximum operating voltage of 2.5 Volts to the A/D converter.

TIMING CIRCUITS

The timing circuits will consist of a signal from the synchronous chopper and the digital control clock. The chopper signal will control the sample & hold circuits, synchronize the multiplexer and A/D, and update the digital calculation sequence.

A/D CONVERTER

An 8-bit A/D converter, running at 1 kHz, will be used to convert the detector signals for the digital processing. It will automatically set its full scale to be equal to 120% of the signal from the Earth reference detector from the array of interest. This will make the LSB of the converter equivalent to about 0.0039 degrees of displacement.

DIGITAL PROCESSOR

The digital processor will be an Application Specific Integrated Circuit (ASIC) gate array. It will first sort out the information from the four detector arrays. Then it will look for the first detector to reach a threshold of 20% and sum its digital voltage to its digital position providing an horizon position word. Then, it will sum this information over 8 chopper cycles (1 second) and truncate the output to the 0.0039 LSB. This will provide a serial digital output consisting of four 11-bit words stored in a shift register for interrogation by the satellite computer. A data ready bit will be provided so that the register won't be read while it's being updated.

INTERFACE CIRCUITS

The interface circuits, drivers and receivers, will be outside the ASIC and tailored to the customers requirements.

POWER SUPPLY

The power supply will use a hybrid switching regulator with discrete transformer/output circuits to minimize its size. The detectors and analog circuits will require a +9 Volt supply and the digital circuits +5 Volts.

LOW ACCURACY SENSOR CIRCUITS

The Low Accuracy version of the LCES will have a comparitor instead of the differential amplifier to compare each detector with the space reference detector. These outputs are sent in parallel through a buffer to the output shift register. The information is then read by the spacecraft in the same manner as the high accuracy version. This requires 8 bits for each array.

ACQUISITION CIRCUITS

For acquisition, the opposing space reference detectors and separate acquisition detectors are sent to comparitors and then added to the output shift register. This will require 8 bits for GEO and 4 bits for LEO operation. These circuits are not shown in the Block Diagrams.

PERFORMANCE ANALYSES

NOISE EQUIVALENT ANGLE, ONE DETECTOR

The first calculation will be to size the field-of-view. If a detector and the adjacent gap cover an angle of 1.0 deg, at 8 degrees off axis, then the focal length, f, of the lens should be

$$f = (0.5+0.1)\text{mm} / (\tan 9 - \tan 8) = 34 \text{ mm}$$

If we define P_d as the difference between the nominal power on a fully exposed detector on the Earth and the power on a detector viewing space, P_d for LEO would then be

$$P_d = LA\Omega TM$$

where:

L = radiance from Earth = 300 μW $sr^{-1}cm^{-2}$

A = aperture area = $\pi \times 3.44^2 \text{ cm}^2 / 4 = 9.29 \text{ cm}^2$

Ω = field-of-view = $0.5^2 / 34^2 = 2.16\times10^{-4}$ sr

T = transmission of optics = $T_1T_2T_3$

T_1 = aperture reduction of pyramid = 0.25

T_2 = reflection of pyramid = 0.90

T_3 = transmission of lens = 0.80

M = modulation factor of chopper = 0.40

Therefore, $P_d = 4.32 \times 10^{-8}$ W

The noise equivalent angle, at the detector, for a 1 Hz bandwidth would be

$$NEA_d = (NEP/P_d)S$$

where: S = the slope at threshold of the detector signal; from Figure 3, S = the displacement required for a full detector signal = 5/6 degree.

therefore, for polymer film the $NEA_d = 0.023$ degrees rms and for lithium tantalate the $NEA_d = 0.015$ degrees rms

NOISE EQUIVALENT ANGLE, ATTITUDE CALCULATION

The NEA for the sensor under normal 4-array operation would be

$$NEA = \{0.707(4NEA_d^2)^{1/2}\}/4 = 0.354NEA_d = 8.2 \times 10^{-3} \text{ degrees rms for polymer and } = 5.5 \times 10^{-3} \text{ degrees rms for Lith. Tant.}$$

RADIANCE/CLOUD VARIATIONS

The effect on the Pitch and Roll calculations of radiance gradiants across the Earth were calculated for 5% and 10% gradiants at both GEO and LEO conditions was analyzed. As expected, the GEO condition was worse since the detectors cover more of the gradiant from that orbit.

RADIANCE GRADIANT EFFECTS

Radiance	GEO		LEO	
Gradient	Pitch	Roll	Pitch	Roll
5%	0.0027	0.0027	0.0022	0.0022
10%	0.0057	0.0057	0.0044	0.0044

The cloud effects were determined by placing the worse case, high altitude cloud first at the horizon and then at the Earth reference detector. The cloud covered the entire detector. This time, again as expected, the greatest effect was at LEO since the signal is not attenuated by as much CO_2 and the horizon detector was effected the most since the influence is direct.

CLOUD EFFECTS

Cloud at	GEO		LEO	
Detector	Pitch	Roll	Pitch	Roll
Horizon	0.0074	0.0074	0.0127	0.0127
Earth Ref	0.0040	0.0040	0.0101	0.0101

ELLIPTICITY

For low altitude orbits the Earth's elliptical shape will cause an error as a function of latitude and inclination. The worst case situation is for a polar orbit. For an altitude of 400 nmi, the error varies from 0 to 0.15 degrees as a function of latitude.

1991 DEVELOPMENT PROGRAM

DETECTOR TESTING

A brassboard sensor was designed and fabricated, using an available 38 mm focal length F/1.0 lens and an 8 Hz chopper design. Two 8-element detector arrays were purchased from Servo Corporation, a lithium tantalate and a polymer film design. Both detectors were tested for linearity and noise. The electronics, through the multiplexer, were also obtained from Servo. An 8 bit A/D converter, clocking circuits, and computer interface circuits were supplied by LMSC. An IBM PC was used to collect the data, convert it to angular format, and perform analyses on it. The results of the testing is described below.

LINEARITY

The detectors, as received from Servo, did not have uniform gain. However, there were adjustable gain amplifiers which allowed us to balance the outputs for a reasonably linear result. Figure 6 illustrates a typical performance against a simulated Earth target after adjustment. Detector 1 was used as the space reference and detector 7 was used as the Earth reference. The results are for four of the remaining detectors. At the midpoints of each detector they are within 0.05 degrees of matching the input. The space between the detectors is not flat because of the optical aberrations.

NOISE

The noise was measured for a 1 Hz average, in the the same test set up as linearity and with a blackbody, by taking 1000 data samples of 8 readings and computing the rms. The results for the various tests have been averaged and they give a 0.024 degrees rms LEO, 0.006 degrees rms GEO for the polymer and 0.016 degrees rms LEO, 0.004 degrees rms GEO for the lithium tantalate. The LEO numbers are similar to those calculated above.

1992 DEVELOPMENT PROGRAM

The plans for 1992 are to build the opto-mechanical parts (those forward of the detectors) in flight-like configuration, build a 40 element (4 x 9 + 4) focal plane, and execute the electronic design with discrete parts. The ASIC designs for the electronics would wait until a flight program is funded. This engineering model would then be subjected to the same functional testing as flight hardware. Since the testing is not completed at the time of this paper, an adendum will be available for those who request it from the author at 2 Sandstone, Portola Valley, CA 94028.

CONCLUSIONS

The work that has been performed to date has demonstrated that this versatile, low cost, design is feasible. The next step is to qualify the hardware and develop the low cost assembly and test processes which will make the hardware available for use.

ACKNOWLEDGMENTS

The author would like to thank Alan Doctor and the Servo Corporation's designers for adjusting to the many iterations of the focal plane configuration. I would also like to thank Basil Lawson, Paul Lee, Ed Louie, Joe Tsou, and Ken Yang of Lockheed for their design and analysis contributions and Stan Hammond for his proofing and suggestions.