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CLOUD TOP SCANNING RADIOMETER (CTS)

FINAL REPORT

JUNE 1978

DOCUMENT No. 7804-5

HONEYWELL
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Lexington, Massachusetts 02173
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SECTION I
INTRODUCTION AND SUMMARY

In accordance with the specifications of contract number NAS5-22459, awarded by the Goddard Space Flight Center (GSFC), the Honeywell Electro-Optics Center has designed, built and tested a scanning radiometer, the Cloud Top Scanner (CTS), to be used for measuring cloud radiances in each of three spectral regions. This final report describes the instrument design and presents system test and calibration data.

The CTS has been designed to be a rugged and versatile scientific instrument which will be readily adaptable to minor changes of mission or experiment.

Significant features incorporated in the instrument design are:

- Flexibility and growth potential through use of easily replaceable modular detectors and filters.
- Full aperture, multilevel inflight calibration.
- Inherent channel registration through employment of a single shared field stop.
- Radiometric sensitivity margin in a compact optical design through use of Honeywell developed (Hg,Cd)Te detectors and preamplifiers.
SECTION 2
REQUIREMENTS

Scientific objectives to precisely image and accurately measure cloud radiances in three spectral regions dictated performance requirements of the Cloud Top Scanner.

2.1 SCIENTIFIC REQUIREMENTS

The scientific purposes of the Cloud Top Scanner (CTS) require that infrared and visible energy be collected from the same instantaneous field of view and that a wide swath width be employed so that efficient ground or cloud area coverage is obtained. In addition, clouds are to be imaged in three dimensions so that the relationship between cloud motions and winds can be studied as well as measuring cumulonimbus cloud top height and localized cumulonimbus upper surface temperature changes so that their relationship to severe storms can be studied. For these purposes, it is necessary to make radiometric measurements in a water vapor absorption band so that the clouds will appear opaque against the earth surface background. The CTS Channel 2 band of 6.6 to 6.9 μm is well suited for this purpose because it is both a strong absorption band and because it is in an unambiguous region of the spectrum. See Figure 2-1.

The presence of a visible spectral band allows correction of radiometric data for solar effects and allows the further study of the Shenk-Curran method of determining cirrus cloud top height. Since high thin clouds contain ice crystal platelets which can become aligned by electrostatic and other forces, these clouds can deviate significantly from blackbody behavior. The measurement of cloud reflectance in the 0.55 to 0.75 μm band (CTS Channel 1) allows a correction to be made to the infrared radiance measurements and the blackbody temperature calculation is much improved.

Channel 3 operates in the 10.5 μm to 12.5 μm region. This is a region of high atmospheric transmittance and is useful, therefore, in measuring earth or sea surface radiances.

2-1
7804-5
Figure 2-1: Atmospheric Transmittance for a Vertical Path to Space from Sea Level for Six Model Atmospheres.
Scientific objectives require precise radiometry so that in the design of the CTS instrument, emphasis was placed on calibration accuracy and system linearity.

2.2 SYSTEM PERFORMANCE REQUIREMENTS

Performance requirements are derived from the scientific objectives. Instrument design was configured to insure meeting all scientific objectives and all requirements given in the work statement. Table 2-1 is a summary of system specifications.
<table>
<thead>
<tr>
<th>Specification</th>
<th>Channel Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Radiometric response</td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.32 W/m²-sr (signal)</td>
</tr>
<tr>
<td>Maximum Signal</td>
<td>96.1 W/m²-sr</td>
</tr>
<tr>
<td>Linearity (Deviation from Least Squares)</td>
<td>± 2%</td>
</tr>
<tr>
<td>Polarization Sensitivity</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>Spectral Response</td>
<td>0.55 ≤ λ(μm) ≤ 0.75</td>
</tr>
<tr>
<td>Spatial Response</td>
<td></td>
</tr>
<tr>
<td>IFOV</td>
<td>6.2 mr</td>
</tr>
<tr>
<td>FOV</td>
<td>± 60°</td>
</tr>
<tr>
<td>MTF @ 1 IFOV</td>
<td>≥ 0.35</td>
</tr>
<tr>
<td>IFOV Registration</td>
<td>0.6</td>
</tr>
<tr>
<td>Calibration</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 3% of full scale</td>
</tr>
<tr>
<td>Repeatability</td>
<td>± 1% of full scale</td>
</tr>
</tbody>
</table>
SECTION 3
INSTRUMENT DESIGN

3.1 SYSTEM DESCRIPTION

The Cloud Top Scanning Radiometer (CTS) is a three-channel absolute radiometer designed to scan clouds while looking downwards from an RB57F aircraft flying at 60,000 feet altitude. Two infrared channels and one visible channel have 6.2 milliradian IFOV and are scanned laterally to the direction of aircraft motion in a single-line scan having 120-degree swath width. This scanning pattern coupled with the aircraft motion provides an effective raster scan of clouds against the earth background, giving information on cloud temperature distribution and structure. The two infrared channels of the CTS system have been chosen in the 6.6-6.9 \textmu m water-vapor absorption band (Channel 2) and in the atmospheric window region at 10.5-12.5 \textmu m (Channel 3). In the former the clouds will appear as opaque against the earth background whereas in the latter, radiometric imaging of the earth's surface is possible, even for regions of high thin cirrus clouds. The visible channel (Channel 1, 0.55-0.75 \textmu m) records reflected and scattered sunlight from the cloud/earth scene.

A composite system drawing is shown in Figure 3-1. Figure 3-2 is a system block diagram.

A flat scanning mirror set at 45 degrees scans a 120-degree arc below the instrument and fills the 8-inch aperture of a Cassegrain telescope. A common field stop defines the common instantaneous field-of-view of all three spectral bands and effectively isolates the rear optics from stray radiation. A rotating chopper wheel modulates the radiation after it leaves the field stop to permit ac coupling of the signal electronics and eliminate detector 1/f noise.

A gold coated beamsplitter separated the IR channels from the visual channel by transmitting Channel 1 signals (0.55 \textmu m to 0.75 \textmu m) while reflecting the longer wavelengths of Channels 2 (6.6 \textmu m to 6.9 \textmu m) and Channel 3 (10.5 \textmu m to 12.5 \textmu m).
Figure 3-2  CTS System Block Diagram
The image of the common field stop is relayed to each detector by collimating and recollecting optics in each channel. Spectral filters are located in each collimated relay beam and can be easily changed when required by the experiments.

The (Hg,Cd)Te infrared detectors are mounted in glass liquid nitrogen dewars with over 8 hours hold time. Each is potted inside a metal housing to provide a rugged and easily replaceable unit. Metal mirrors are used throughout the design for ease of mounting and because of their ability to maintain optical quality over a considerable range of temperature. The optics are supported by a rigid aluminum casting, which also facilitate assembly.

In order to achieve the full benefits of an accurate primary calibration, the CTS has been designed for high inflight stability. Stability is achieved by clamping the chopper radianc signs to a known voltage level. The chopper is effectively used as a transfer standard between the unknown scene radiance and the in-flight calibration sources (IFC sources). Inflight calibration checks are performed in channels 2 and 3 during the backside portion of each scan. A hot blackbody and cold blackbody source are scanned in succession by the rotating scan mirror.

The instrument electronics, comprised of linear and digital circuitry, performs the required signal conditioning, timing, and control functions.

Table 3-1 is a summary of system weight and power requirements.

3.1.1 Radiometric Analysis

Radiometric sensitivity of the CTS is defined by the following equations:

Visible Channel

\[
\text{NEA} = \frac{(\text{NEP/Hz}^2) \Delta f \alpha_{ch} \alpha_e}{A_o \beta^2 \tau_o}
\]  

(1)
### Table 3-1 WEIGHT, SIZE AND POWER SUPPLY

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TOTAL</th>
<th>SCANNER</th>
<th>ELECTRONIC BOX</th>
<th>HOT BB CONTROLLER</th>
<th>COLD BB CONTROLLER</th>
<th>HEAT EXCHANGER</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIMENSIONS W x L x H</td>
<td>11 ft³</td>
<td>18 1/2&quot; x 30&quot; x 21&quot;</td>
<td>12&quot; x 18&quot; x 13&quot;</td>
<td>19&quot; x 9&quot; x 3 1/2&quot;</td>
<td>7&quot; x 14&quot; x 19&quot;</td>
<td>8&quot; x 8&quot; x 8&quot;</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>191 POUNDS</td>
<td>110 POUNDS</td>
<td>40 POUNDS</td>
<td>6 POUNDS</td>
<td>15 POUNDS</td>
<td>20 POUNDS</td>
</tr>
<tr>
<td>POWER GROUND OPERATION</td>
<td>200 W.D.C.</td>
<td>40 W.D.C.</td>
<td>160 W.D.C.</td>
<td>200 W.A.C.</td>
<td>100 W.A.C.</td>
<td>0</td>
</tr>
<tr>
<td>POWER FLIGHT</td>
<td>120 W.D.C.</td>
<td>20 W.D.C.</td>
<td>100 W.D.C.</td>
<td>200 W.A.C.</td>
<td>500 W.A.C.</td>
<td>100 W.A.C.</td>
</tr>
<tr>
<td>POWER DESCENT</td>
<td>750 W.A.C.</td>
<td>550 W.A.C.</td>
<td>0</td>
<td>100 W.A.C.</td>
<td>100 W.A.C.</td>
<td>0</td>
</tr>
</tbody>
</table>
Infrared Channels

\[
\text{NEAT} = \frac{A_d^{\frac{1}{2}} \Delta f \Delta n^{\frac{1}{2}} \sigma_{ch} \alpha}{\left(\frac{\delta N}{\delta T}\right)_{\Delta \lambda} \omega^2 A_o D^* \tau_o}
\]  

(2)

Table 3-2 gives the design parameters for the pertinent terms in equations 1 and 2, in order to satisfy a 0.32 watt/m²-s NEATN (Channel 1) and an NEAT at 185 K of 1 K and 0.3 K, respectively, for Channels 2 and 3. An eight-inch aperture (292 cm²) provides sufficient design margin.

In the sensitivity calculations, several considerations are worth noting. First, the noise bandwidth has been calculated to be 1012 Hz which assumes a four-pole Butterworth noise limiting filter which degrades the information bandwidth by a factor of 1.1. Second, the chopper has an rms conversion factor \( \alpha_{ch} \) which degrades the signal. For perfect square wave chopping \( \alpha_{ch} = 1.57 \), where the chopper opening is many times the beamwidth. In the proposed CTS design, the chopper opening is 3.3 times the beamwidth so that the resulting trapezoidal waveform is close to the triangular wave resulting for a 1:1 size ratio. The degradation factor for this design is \( \alpha_{ch} = 1.9 \), as shown in Figure 3-3. Third, the electronic noise in the processing circuits also add noise. The value of \( \alpha_e = 1.7 \) is used here in agreement with that suggested by L. Goldberg in his discussion of signal-to-noise in the AVHRR paper, NASA N68-17253.

3.1.2 Detector Requirements

From the equation in Table 3-2, \( D^*_\Delta \lambda \) requirements are derived for both (Hg,Cd)Te detectors. Specifications for these are given in Table 3-3. Sensitivity requirements for the silicon detector is given by:

\[
\text{NEP}^i = 1.8 \times 10^{-11} \text{ watts/Hz}^{\frac{1}{2}}
\]  

(3)

3-6
### Table 3-2 SENSITIVITY ANALYSIS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SYMBOL</th>
<th>CH 1</th>
<th>CH 2</th>
<th>CH 3</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector-Area</td>
<td>$A_d$</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>cm$^2$</td>
</tr>
<tr>
<td>Noise Bandwidth</td>
<td>$\Delta f_n$</td>
<td>1012</td>
<td>1012</td>
<td>1012</td>
<td>Hz</td>
</tr>
<tr>
<td>Chopper Conversion Factor</td>
<td>$\alpha_{CH}$</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>---</td>
</tr>
<tr>
<td>Electronic Noise Factor</td>
<td>$\alpha_e$</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>---</td>
</tr>
<tr>
<td>Incremental Radiance With Temp.</td>
<td>$\frac{\delta N}{\delta T}_{185}$</td>
<td>---</td>
<td>1.58 x $10^{-7}$</td>
<td>4.97 x $10^{-6}$</td>
<td>W/cm$^2$-sr-K$^0$</td>
</tr>
<tr>
<td>Solid Angle</td>
<td>$\Omega$</td>
<td>3.84 x $10^{-5}$</td>
<td>3.84 x $10^{-5}$</td>
<td>3.84 x $10^{-5}$</td>
<td>sr</td>
</tr>
<tr>
<td>Entrance Aperture</td>
<td>$A_o$</td>
<td>324.3</td>
<td>324.3</td>
<td>324.3</td>
<td>cm$^2$</td>
</tr>
<tr>
<td>$D^*\Delta \lambda$</td>
<td>$D^*\Delta \lambda$</td>
<td>---</td>
<td>3.5 x $10^{10}$</td>
<td>1.5 x $10^{10}$</td>
<td>cm-Hz$^{1/2}$/W</td>
</tr>
<tr>
<td>Optical Efficiency</td>
<td>$\tau_0$</td>
<td>0.13/0.16</td>
<td>0.41/0.44</td>
<td>0.28/0.39</td>
<td>---</td>
</tr>
<tr>
<td>Noise Equivalent Power</td>
<td>NEP$'$(CH 1)</td>
<td>1.8 x $10^{-11}$</td>
<td>---</td>
<td>---</td>
<td>W/Hz$^{1/2}$</td>
</tr>
<tr>
<td>Sensitivity Required</td>
<td>NEN (CH 1)</td>
<td>0.32 (goal)</td>
<td>1 K$^0$</td>
<td>0.3 K$^0$</td>
<td>---</td>
</tr>
<tr>
<td>Predicted Sensitivity Spec/Goal</td>
<td>NEN (1) NETD (2,3)</td>
<td>0.011/0.009</td>
<td>0.81/0.76</td>
<td>0.09/0.06</td>
<td>---</td>
</tr>
</tbody>
</table>

\[
\text{NETD} = \frac{A_d^{1/2} \Delta f_n^{1/2} \alpha_{CH} \alpha_e}{\frac{\delta N}{\delta T}_{185} K \Omega A_o \Delta \lambda \tau_0}
\]

\[
\text{NEN} = \frac{(\text{NEP}'') \Delta f_n^{1/2} \alpha_{CH} \alpha_e}{A_o \Sigma \tau_0}
\]
$x = 0.333$
RMS FACTOR
Is 0.372
$a_{ch} = \frac{0.707}{0.372} = 1.9$

Figure 3-3  Chopper RMS Conversion Factor for Square IFOV for Various Chopper Geometrics

3-8
Table 3-3 HCT DETECTOR SPECIFICATION

- **PACKAGE:** GLASS DEWAR SIMILAR TO DLK-51F
  HOUSING NOT DETERMINED
- **DETECTORS:** 1 EACH 6.6-6.9 μm AND 10.5-12.5 μm
- **REQUIREMENTS:**

<table>
<thead>
<tr>
<th>6.6-6.9-μm CHANNEL</th>
<th>10.5-12.5-μm CHANNEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x \sim 0.25)</td>
<td>(x \leq 0.2)</td>
</tr>
<tr>
<td>0.080 x 0.080 (± 0.002)</td>
<td>0.080 x 0.080 (+ 0.002)</td>
</tr>
<tr>
<td>77°K OPERATION</td>
<td>77°K OPERATION</td>
</tr>
<tr>
<td>300°K B.G.</td>
<td>300°K B.G.</td>
</tr>
<tr>
<td>60° FOV</td>
<td>60° FOV</td>
</tr>
<tr>
<td>( D^* \lambda ) (6.6-6.9, 4 kHz, 500°K) \geq 3.5 \times 10^{10}</td>
<td>( D^* \lambda ) (10.5-12.5, 4 kHz, 500°K) \geq 1.5 \times 10^{10}</td>
</tr>
<tr>
<td>( R \lambda ) (6.6-6.9) \geq 200 V/W</td>
<td>( R \lambda ) (10.5-12.5) \geq 200 V/W</td>
</tr>
<tr>
<td>( 20 \leq R_D \leq 100 ) (50 typ)</td>
<td>( 10 \leq R_D \leq 100 ) (35 typ)</td>
</tr>
<tr>
<td>1/f KNEE \leq 2 kHz</td>
<td>1/f KNEE \leq 2 kHz</td>
</tr>
<tr>
<td>V_N \sim 3 \times 10^{-9}</td>
<td>V_N \sim 3.4 \times 10^{-9}</td>
</tr>
<tr>
<td>WINDOW: AR-COATED Ge</td>
<td>WINDOW: AR-COATED Ge</td>
</tr>
</tbody>
</table>

3-9

7804-5
Silicon detectors with the above performance are readily available "off-the-shelf".

3.1.3 Spatial Response

Spatial response of a scanning system is accurately described by its modulation transfer function (MTF). The MTF is the instrument's amplitude response to a set of spatial frequencies in object space.

System MTF can be calculated by taking the product of the Fourier transforms of optics blur and detector spatial and temporal response and multiplying the result with the electronics frequency response. The resulting graph is shown for channel I in Figure 3-4.

3.1.4 Calibration

Instrument in-flight-calibration consists of two large area blackbody sources located in object space as shown in Figure 3-5. These sources are large enough to completely fill the field of view for a minimum calibration dwell angle of 7.2 degrees. Calibration occurs once per scan line. Table 3-4 summarizes specifications for the two sources and predicted system accuracy for the two infrared channels. A detailed description of the calibration sources can be found in Appendix A.

Channel I is not calibrated during flight. Stability of this channel is obtained, however, by accurately controlling the silicon detector temperature to minimize responsivity variations.

A rotating emissive chopper blade serves as a reference system during the active scan time and is used to minimize effects of 1/f noise and low frequency system drifts.
Table 3-4  CTS IN-FLIGHT CALIBRATION

- CALIBRATION METHOD: TWO LARGE AREA BLACKBODIES IN OBJECT SPACE

- BLACKBODIES DESCRIPTION

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOT BLACKBODY (BB_H) TEMPERATURE</td>
<td>280 °K</td>
</tr>
<tr>
<td>COLD BLACKBODY (BB_C) TEMPERATURE</td>
<td>20 K below ambient</td>
</tr>
<tr>
<td>EMISSIVITY</td>
<td>≥0.98</td>
</tr>
<tr>
<td>BB TEMPERATURE MEASUREMENT ACCURACY</td>
<td>± 0.05 K</td>
</tr>
<tr>
<td>CALIBRATION DWELL ANGLE</td>
<td>7.2°</td>
</tr>
</tbody>
</table>

- SYSTEM ABSOLUTE ACCURACY

<table>
<thead>
<tr>
<th>Channel</th>
<th>Accuracy @ Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHANNEL 2</td>
<td>± 1.9 K @ 185 °K</td>
</tr>
<tr>
<td>CHANNEL 3</td>
<td>± 0.9 K @ 185 °K</td>
</tr>
</tbody>
</table>
3.1.4.1 **Error Analysis**

In determining the optimum calibration and chopper configuration, a detailed error analysis was performed to arrive at comparative performance estimates for various systems. Several methods have been investigated including the use of large area blackbodies, multiple small area blackbodies in object space, and the proposed scheme of small area blackbodies in a focused beam.

A summary of the equations is given in the following section.

3.1.4.1.1 **Derivation of Equations**

Symbols used in the derivation and their definitions are listed below:

- **N** = Radiance (watts/cm\(^2\) - sr)
- **T** = Temperature (K)
- **\(\varepsilon_e\)** = Effective emittance of in-flight calibration source
- **V** = Signal (volts)
- **m** = Calibration curve slope (W/cm\(^2\) - sr/volts)
- **N_0** = Calibration curve offset (W/cm\(^2\) - sr)
- **N_{EN}** = Noise equivalent radiance
- **\(\tau\)** = Transmittance
- **\(\rho\)** = Reflectance
- **H** = High Calibration Source
- **L** = Low Calibration Source
- **HNG** = Housing
- **R** = Reference Source
- **RLOPT** = Reflective Optics (Telescope)
- **P** = Primary Calibration Source (Ground Calibration)
- **IFC** = In Flight Calibration
- **\(\delta\)** = Error or unmonitored change in quantity
- **t** = Target or object to be measured
- **A** = Ambient of primary calibration source
- \(\frac{\partial N}{\partial T}\) = Incremental radiance per K at temperature T (W/cm\(^2\) - sr - K)
Figure 3-6 shows the expected Cloud Top Scanner calibration curve for Channel 3 where input signal radiance (measured at the entrance aperture) is plotted as a function of output voltage. Voltage levels for both in-flight calibration (IFC) sources are indicated ($V_H$, $V_L$).

The actual slope and intercept of the calibration curve is determined in flight by means of the IFC sources.

Target radiance is given by the following equation:

$$N_t = mV_t + N_o$$ (4)

The error in target radiance is then given by:

$$\delta N_t = m\delta V_t + V_t \delta m + \delta N_o + \delta N_{PCAL}$$ (5)

where $N_{PCAL}$ is the radiance error in primary instrument calibration. Since all of the error terms in the above equation are nearly independent, the most probable system error is the root sum squared value:

$$\delta N_t = \left\{ (m\delta V_t)^2 + (V_t \delta m)^2 + (\delta N_o)^2 + (\delta N_{PCAL})^2 \right\}^{1/2}$$ (6)

3.1.4.1.2 **Slope ($m$)**

Slope of the calibration curve is determined by measuring the radiance signal from the IFC sources and comparing these to readings from the calibration temperature monitors:

$$m = \frac{e(N_H - N_L)}{V_H - V_L}$$ (7)
Figure 3- 6 Typical CTS Calibration Curve
where \( N_H \) and \( N_L \) are the in-band radiance of the high and low calibration sources, respectively calculated from the IFC temperature.

\[
V_H = \frac{N_H - N_{185}}{m'}; \quad V_L = \frac{N_L - N_{185}}{m'}
\]  

(8)

\( m' \) = slope of calibration curve obtained during primary ground calibration

\[
m' = \frac{N_{325} - N_{185}}{9.8 \text{ volts}}
\]  

(9)

3.1.4.1.3 Error in Measuring Target Voltage \((\delta V_t)\)

\[
\delta V_t = \frac{1}{m} \left\{ N_{EN}^2 + \delta N_R^2 + \left( \delta (1 - \tau_{RLOPT}) N_{HNG} \right)^2 \right\}^{1/2}
\]  

(10)

\[
\delta N_R = \delta T_R \frac{\partial N}{\partial T} \bigg|_R, \text{ where } \delta T_R = \text{change in reference temperature between time of in-flight calibration and time of data taking;}
\]

\[
\delta V_t = \frac{1}{m} \left\{ N_{EN}^2 + \left[ (\delta T_R \frac{\partial N}{\partial T})_R \right]^2 + \left(1 - \tau_{RLOPT}\right) \delta N_{HNG} - N_{HNG} \right\}^{1/2}
\]  

(11)

where \( \delta T_{RLOPT} = \) change in telescope reflectance between IFC time and data time

\[
\delta T_{RLOPT} \approx 0
\]  

(12)

\[
\delta N_{HNG}' = \text{change in housing radiance between IFC time and data time}
\]

\[
\delta N_{HNG}' = \delta T_{HNG}' \frac{\partial N}{\partial T} \bigg|_{HNG}
\]

\[
\delta T_{HNG}' = \delta T_R \text{ and } \frac{\partial N}{\partial T} \bigg|_{HNG} \approx \frac{\partial N}{\partial T} \bigg|_R
\]  

(13)

because the housing and chopper reference are at approximately the same temperature.

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7804-5
3.1.4.1.4 **Target Voltage** \((V_t)\)

\[
V_t = \frac{1}{m} (N_t - N_{185})
\]  

(14)

at a target temperature \(T_t = 185 \text{ K}\), \(N_t = N_{185}\) and \(V_t = 0\)

3.1.4.1.5 **Error in Slope** \((\delta m)\)

\[
m = \frac{\epsilon_e (N_H - N_L)}{V_H - V_L}
\]  

(15)

\[
\delta m = \frac{\delta \epsilon_e (N_H - N_L) + \epsilon_e \delta (N_H - N_L)}{V_H - V_L} - \frac{\epsilon_e (N_H - N_L)}{(V_H - V_t)^2} \delta (V_H - V_L)
\]

(16)

\[
\frac{N_H - N_L}{V_H - V_L} = m' \approx m
\]

\[
\delta (V_H - V_L) = \sqrt{2} \text{ NEN/mn}^{1/2}
\]

\[n = \text{number of dwell times on the IFC sources.}\]

\[
\delta m = m \delta \epsilon_e + \left[ \epsilon_e \frac{\epsilon_e}{V_H - V_L} \right] \left[ \delta T_{\text{IFC}} \left( \frac{\partial N}{\partial t} \right) \right]_{H} - \left[ \delta T_{\text{IFC}} \left( \frac{\partial N}{\partial t} \right) \right]_{L} \sqrt{\frac{2 \text{ NEN}}{n^{1/2}}} \]

(17)

3.1.4.1.6 **Error in Offset Radiance** \((\delta N_o)\)

\[
\epsilon_e \ N_H + (1 - \epsilon_e) \ N_{\text{HNG}} = m \ V_H - N_o
\]

(from graph)  

(18)

\[
\epsilon_e \ N_L + (1 - \epsilon_e) \ N_{\text{LNG}} = m \ V_L - N_o
\]

3-18

7804-5
where

\[
\delta N_{\text{HNG}} = \delta N_{\text{HNG}, \delta T} \left|_{\delta T} \right.
\]

\[
\delta T_{\text{HNG}} = \text{error in determining housing temperature}
\]

\[
\delta T_{\text{IFC}} = \text{error in measuring IFC temperature}
\]

3.1.4.1.7 Error during Primary Ground Calibration (\(\delta N_p\))

\[
\delta N_p = \varepsilon_{\text{ef}} \varepsilon_{\text{f}} \frac{\partial N}{\partial T} \left[ p + N_p \delta e_{\text{ef}} \left( 1 - e_{\text{ef}} \right) \right] \delta N_A + N_A \delta (1 - e_{\text{ef}})
\]

after rearranging terms and taking the RSS value.

\[
N_p = \left\{ \left[ \varepsilon_{\text{ef}} \frac{\partial N}{\partial T} \right] p + \delta T_A \left[ \delta e_{\text{ef}} \left( 1 - e_{\text{ef}} \right) \right] \right\}^2 + \left[ \delta e_{\text{ef}} \left( N_p - N_A \right) \right] ^2 \right\}^{1/2}
\]

(24)

3.1.4.1.8 Error in Target Temperature (\(T_t\))

\[
\delta T_t = N_t / \left. \frac{\partial N}{\partial T} \right| t, \quad \text{where } T_t = 185 \text{ K}
\]

(25)

3.2 OPTICAL DESIGN

The overall CTS optical system raytrace is shown in Figure 3-7 and an optical elements list is given in Table 3-5. The wide field of view (FOV) requirement (±60°) necessitated the use of an object plane reflective scanner.

An 8-inch aperture Cassegrain telescope has been chosen for the main collecting optics, its f/1.0 primary mirror (a parabola) and a hyperbolic secondary mirror provide a very compact collecting system, while the f/3 speed at the field stop allows sufficient back focus for the rest of the system to be placed in an optimum location.
<table>
<thead>
<tr>
<th>ELEMENT NUMBER</th>
<th>FUNCTION</th>
<th>MATERIAL</th>
<th>TRANSMITTANCE SPEC</th>
<th>TRANSMITTANCE GOAL</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>SCANNER</td>
<td>Au COATED Be</td>
<td>CH 1</td>
<td>0.85</td>
</tr>
<tr>
<td>2</td>
<td>PRIMARY</td>
<td>Au COATED A1</td>
<td>CH 2</td>
<td>0.97</td>
</tr>
<tr>
<td>3</td>
<td>SECONDARY</td>
<td>Au COATED A1</td>
<td>CH 3</td>
<td>0.97</td>
</tr>
<tr>
<td>4</td>
<td>BEAMSPLITTER (1)</td>
<td>Au COATED BX-7</td>
<td>CH 1</td>
<td>0.60</td>
</tr>
<tr>
<td>5</td>
<td>BEAMSPLITTER (2)</td>
<td>GERMANIUM</td>
<td>CH 2</td>
<td>0.95</td>
</tr>
<tr>
<td>6</td>
<td>LENS CH 3</td>
<td>GERMANIUM</td>
<td>CH 3</td>
<td>0.95</td>
</tr>
<tr>
<td>7</td>
<td>FILTER CH 3</td>
<td>GERMANIUM</td>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td>8</td>
<td>LENS CH 3</td>
<td>GERMANIUM</td>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td>9</td>
<td>LENS CH 2</td>
<td>GERMANIUM</td>
<td></td>
<td>0.92</td>
</tr>
<tr>
<td>10</td>
<td>FILTER CH 2</td>
<td>GERMANIUM</td>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td>11</td>
<td>MIRROR CH 2</td>
<td>Au COATED A1</td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>12</td>
<td>LENS CH 2</td>
<td>GERMANIUM</td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>13</td>
<td>LENS CH 1</td>
<td>LAKN19</td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>14</td>
<td>POLARIZER CH 1</td>
<td>BK-7</td>
<td></td>
<td>0.70</td>
</tr>
<tr>
<td>15</td>
<td>FILTER CH 1</td>
<td>BK-7</td>
<td></td>
<td>0.85</td>
</tr>
<tr>
<td>16</td>
<td>LENS CH 1</td>
<td>LAKN19</td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>17</td>
<td>LENS CH 1</td>
<td>LAKN19</td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>SYSTEM TRANSMITTANCE</td>
<td></td>
<td></td>
<td>CH 1</td>
<td>0.16</td>
</tr>
<tr>
<td>UNOBSCURED AREA</td>
<td></td>
<td></td>
<td>CH 2</td>
<td>0.796</td>
</tr>
<tr>
<td>SYSTEM THROUGHPUT</td>
<td></td>
<td></td>
<td>CH 3</td>
<td>0.127</td>
</tr>
</tbody>
</table>
The classical Cassegrain design for the CTS collector was chosen because it easily meets the performance requirement of 0.10-milliradian blur circle over the IFOV. On axis the performance is geometrically perfect and, therefore, gives a diffraction-limited system at all wavelengths. At the center of the sides of the square 6.2-milliradian IFOV, the geometrical spot size is 0.06 milliradian due to coma, and it reaches 0.09 milliradian at the diagonal corners of the IFOV. Other choices are available for the mirror surface figures than the classical parabola-hyperbola combination of the Cassegrain. A Ritchey-Cretien design, consisting of two hyperbolic mirrors, would have no coma, but would be more expensive and give essentially no improvement in the total system transfer function. This is because the transfer function is not primarily limited by the optics, but rather by the electronics and the IFOV size. A cheaper design of the Doll-Kirkham type with an elliptical primary mirror and a spherical secondary mirror would have too much coma to meet the 0.10-milliradian blur circle size, although the low frequency optical transfer function would not be appreciably degraded.

The f/3 system appears to be an optimum choice on many counts. At speeds faster than f/3, the classical Cassegrain type telescope would have more than 0.10-milliradian of coma over the 6.2-milliradian IFOV. Slower speeds, like f/4 or f/5, would give better performance, but would increase the sensitivity of the telescope to misalignment of the secondary mirror.

By forming an image onto a field stop and then reimaging this onto the detectors, many problems are avoided and a simple system results. The field stop approach automatically makes all the spectral channels fall into perfect spatial registration in object space. Furthermore, a high quality image is only needed at the field stop since the system transfer function is determined by the transfer function at that point in the system. Following the field stop, we are only interested in collecting most of the energy onto the detectors, not in maintaining resolution. This means that relatively simple recollecting optics can be employed without the high performance requirements of the front telescope.

After the field stop, the various spectral channels are split apart by means of dichroic beamsplitters (elements 4 and 5, Figure 3-7). The beamsplitters are in diverging light (f/3 beam) as shown, but do not introduce an objectionable amount of aberration.
Since we are only concerned with energy collection and not MTF at this point, the image quality can be quite coarse compared to the front telescope, and still have most of the energy fall on the detectors (oversized).

Lenses are used to collimate the light in each channel after the dichroic splitting, and then refocus onto the detectors at f/1.0. Figures 3–8 through 3–10 show the detailed optical train for each of the three channels along with radii and spacing of elements. Two germanium lenses suffice to provide a blur circle size of less than 1/3 of IFOV for the two infrared channels. When integrated over the detector size, this gives almost all of the energy within the IFOV. For the visible channel, much less energy is required because of the sensitivity involved. A smaller portion of the energy is selected from the f/3 diverging beam and focused on the detector by three glass lenses.

Since the light for this channel passes through a dichroic filter (surfaces 4 and 5), which may produce slight polarization, a compensating plate (surfaces 8 and 9) has been added which is tilted about an axis perpendicular to the tilt axis of the beamsplitter. The polarization effects of the compensator will render the final beam unpolarized. Three lenses for glass type LAKN19 are used along with a bandpass filter located in the collimated portion of the beam.

In all three channels, the bandpass filters are situated so as to be easily removable and replaceable if the wavelengths of interest should be rechosen. The germanium lenses have essentially no change in focus as a function of wavelength while the glass lenses for the visible channel already are covering half of the visible spectrum with no problem. Any reasonable wavelength shift will still result in most of the energy falling on the detector.

Since the field stop is many times larger than the blur circle diameter, diffraction effects at the edge of the field contribute only a small blurring of the total energy collected. Registration thus largely depends on the electronic delays, which are matched to meet the 0.6 milliradian specification.

Layout of the two infrared channels allows the use of downlooking dewars for the Mercury Cadmium Telluride (Hg,Cd)Te detectors.
<table>
<thead>
<tr>
<th>Surface No.</th>
<th>Radius</th>
<th>Spacing</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-16.0</td>
<td>-5.5</td>
<td>Parabola CC = -1</td>
</tr>
<tr>
<td>2</td>
<td>-7.50008</td>
<td>7.49985</td>
<td>Hyberbola CC = -4.000121</td>
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<td>3</td>
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<td>0.7</td>
<td>Field Stop</td>
</tr>
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<td>4</td>
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<td>0.150</td>
<td>Dichroic 45° BK7</td>
</tr>
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</tr>
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<td></td>
</tr>
<tr>
<td>8</td>
<td>0.0</td>
<td>0.100</td>
<td>LAKN19 Lens</td>
</tr>
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<td>9</td>
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<td>1.0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
<td>0.100</td>
<td></td>
</tr>
<tr>
<td>11</td>
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<td>12</td>
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<tr>
<td>18</td>
<td>0.0</td>
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<td></td>
</tr>
</tbody>
</table>

Figure 3-8  CTS Channel 1 Optics
3.2.1 Image Quality

Figure 3-11 shows the shape of the image of points at the corners of the IFOV on the detectors at the best focus position. Due to the aberrations present, if the detector were of exactly the size indicated by first-order optics, some radiation would be lost. The loss would increase if the focus were not perfect, and a study was made to determine the collection efficiency for three different detector sizes as a function of focus error. The results, shown in Figure 3-12, led to the selection of an 0.080-inch detector size. This choice gives minimum detector noise while rendering manufacturing tolerances on the dewar fairly loose; at a defocus of 0.020-inches, the system still collects all the radiation.

3.2.2 Cold Shield

An analysis was performed to determine the sources of self-emitted radiation that could reach the detectors. The optical system was ray traced backwards from the detector. At each surface, the ray positions were compared with the clear aperture of that surface, and, if this was exceeded, the intersection point of those rays falling outside the aperture were assumed to represent potential sources of self-emitted radiation. The resulting map of sources, in the coordinate system of the final recollector lens, is shown in Figures 3-13 and 3-14. The dots on these figures represent rays that were transmitted entirely through the telescope, and the numerals indicate which surface interrupted the ray in question. Surface 3 is the final lens mount, surface 14 is the rear surface of the primary mirror, and surface 15 represents the secondary mirror; rays stopped there fall outside the clear aperture and are not reflected. Surface 16 is the primary mirror and 17 is the obscuration caused by secondary.

It is evident from Figures 3-13 and 3-14 that considerable flux could originate from surfaces 14 and 15. Since these are forward of the chopper, they would contribute false signal.

In order to eliminate this unwanted radiation, we make use of the fact that the recollector optics forms an image of the primary mirror as well as an image of the distant object. The image for the mirror, called the exit pupil of the system, falls a fraction of an inch in front of the detectors. A baffle may be placed at this location, as shown in
Figure 3-11 CTS Detector Image
Figure 3-12 CTS Through Focus Efficiency
Figure 3-13 Detector Field of View Without Cold Shield
Figure 3-14 Detector Field of View Without Cold Shield
Figures 3-15 and 3-16, which will completely obstruct any self-emitted radiation arriving at the detector from around the outside of the beam. (Stray radiation arriving from within the obscuration cone is unaltered). Since the baffle is behind the chopper, any radiation originating on it is not chopped and does not contribute an ac signal. It is even possible to eliminate most of the signal by cooling the baffle. This is not difficult owing to its location within the dewar, and when this technique is employed it is called a cold stop. The optical effect of the cold stop is shown in Figure 3-17. The only significant sources of radiation indicated are the signal itself (dots), the obscuration (18), and the cold shield (3).

3.2.3 Optical Telescope

A tolerance analysis was performed to determine optical sensitivities to manufacturing and alignment errors. Results of this analysis are summarized in Table 3-6. This table lists the allowable variation from the specification during lens fabrication and system alignment.

3.3 MECHANICAL DESIGN

3.3.1 Mechanical Configuration

Figure 3-18 shows the scanner. Figures 3-19 and 3-20 are side views and rear views of the scanner housing respectively. The main scanner structure consists of a single aluminum casting to which the optics, detectors, chopper, and calibration sources are mounted.

Selection of aluminum for the scanner housing minimizes misalignments due to thermal gradients within the scanner. Since the primary and secondary mirrors are also constructed of aluminum, the telescope remains aligned through the specified -40°C to +40°C temperature excursion range.

Figure 3-21 shows the calibration source location with respect to the optical axis and secondary mirror spider.
Figure 3-16  Channel 3 Cold Shield
### Table 3-6 CTS TOLERANCES

<table>
<thead>
<tr>
<th>FOREOPTICS</th>
<th>M₁ M₂</th>
<th>VARIABLE</th>
<th>VALUE</th>
<th>TOLERANCE</th>
</tr>
</thead>
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<tr>
<td>RECOLLECTOR OPTICS</td>
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<td>LENS THICKNESS</td>
<td>---</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>AIR SPACES</td>
<td>---</td>
<td>±0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FILTER THICKNESS</td>
<td>---</td>
<td>±0.010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T.I.R. (WEDGE)</td>
<td>---</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FIGURE</td>
<td>---</td>
<td>5 Fringes to Test Plate, 1/2 Fringe Irreg.</td>
</tr>
<tr>
<td>CH 1</td>
<td></td>
<td>L₁, R₁</td>
<td>23.792</td>
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</tr>
<tr>
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</table>

3-37
Figure 3-20  Scanner Rear View
3.3.1.1 (Hg,Cd)Te Dewars

Figure 3–22 is a detailed drawing of the (Hg,Cd)Te liquid nitrogen (LN$_2$) dewars and housings for channels two and three. To maximize operating time, glass dewars are used as the LN$_2$ reservoir. Machined aluminum housings protect the glass dewars from damage and provide alignment surfaces for each detector.

In order to allow extended operation, the dewar well must be maintained at an ambient pressure of one atmosphere. If pressure were reduced, the LN$_2$ would boil off too quickly thereby shortening operating time. An absolute pressure relief valve mounted on the aluminum housing seals each dewar and maintains pressure within the dewar at 1.2 atmospheres.

3.3.1.2 Visual Detector Mounting

The channel one assembly consists of preamplifiers and optics. All components mount on a support bar shown in Figure 3–23 which is attached to the main casting as shown in Figure 3–18. The center drawing in Figure 3–23 is a cross sectional view of channel I optics showing the collimator lens at left, compensator plate positioned at 45 degrees to the optical axis, two recollecting lenses and detector/preamplifier assembly at the extreme right. Transverse alignment of the detector is achieved by translating the detector/ preamplifier assembly, while focus is optimized by selecting the proper shim dimensions for this assembly.

3.3.1.3 Electronics Assembly

Figure 3–24 shows the electronics assembly revealing locations of electronics boards, power supply and connectors. The base is made of a solid aluminum plate to facilitate heat transfer away from the power supply. No fan is provided because at the flight altitude of 60,000 feet air flow would be a very inefficient cooling method. Cooling is, therefore, achieved only by conduction through the base plate.
Figure 3-22  Channel #2 and #3 Dewar Assembly
Figure 3-25 is an interconnect diagram of the major subassemblies.

3.1.4 Sensor Mounting

Mounting of the sensor within the aircraft POD is shown in Figure 3-26.

3.3.2 Thermal Analysis

A thermal analysis was performed to determine the extent of thermally induced misalignment.

Operation under steady state conditions was analyzed and effects of thermal gradients were investigated. Results of the steady state analysis are given in Table 3-7 showing the expected operational temperatures of elements which can influence radiometric or optical performance. These temperatures are calculated for operation at an altitude of 60,000 feet. The analysis indicated that gradients listed in Table 3-7 have negligible effects on optical and radiometric performance.

In order to determine the need for condensation protection, the instrument temperature profile during descent was calculated as a function of altitude and compared to the dew point. Figures 3-27 and Table 3-8 give results of this calculation. It was determined that by locating blanket heaters in locations described by Table 3-8 condensation can be prevented from forming on critical optical components provided the descent time is longer than 45 minutes.

3.3.3 Structural Analysis

Performance of the CTS system was analyzed for 19 sinusoidal vibration levels and a frequency range of 10 Hz to 2000 Hz. These are worst case conditions for operation at 60,000 feet. Figure 3-28 shows the structural model used to evaluate performance of the scanner assembly. Vibration stresses and deformations due to spin effects on the scan mirror have been calculated and results given in Table 3-9. It can be seen that sufficient
Figure 3-26 Aircraft Mounting
<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>TEMPERATURE - K</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCAN MIRROR</td>
<td>266</td>
</tr>
<tr>
<td>SCAN ELECTRONICS</td>
<td>264</td>
</tr>
<tr>
<td>SECONDARY MIRROR</td>
<td>256</td>
</tr>
<tr>
<td>TELESCOPE</td>
<td>257</td>
</tr>
<tr>
<td>PRIMARY MIRROR</td>
<td>259</td>
</tr>
<tr>
<td>CHOPPER MOTOR</td>
<td>266</td>
</tr>
<tr>
<td>CHOPPER BLADE</td>
<td>257</td>
</tr>
<tr>
<td>TORQUE MOTOR AND ENCODER</td>
<td>287</td>
</tr>
<tr>
<td>DETECTOR AND OPTICS SECTION</td>
<td>257</td>
</tr>
</tbody>
</table>
Data for Mean Annual Atmosphere at 15° North Latitude (GUAM)

Figure 3-27  Cloud Top Scanner Environmental Conditions
Table 3-8 COMPONENT TEMPERATURE VS AIRCRAFT DESCENT TIME

<table>
<thead>
<tr>
<th>Component</th>
<th>Heater Power (watts)</th>
<th>Initial 0.0 hour</th>
<th>Descent Time 0.5 hour</th>
<th>Descent Time 0.75 hour</th>
<th>Descent Time 1.0 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan mirror</td>
<td>58</td>
<td>256</td>
<td>295</td>
<td>315</td>
<td>334</td>
</tr>
<tr>
<td>Secondary mirror</td>
<td>15</td>
<td>256</td>
<td>300</td>
<td>319</td>
<td>337</td>
</tr>
<tr>
<td>Primary mirror</td>
<td>0</td>
<td>256</td>
<td>283</td>
<td>299</td>
<td>315</td>
</tr>
<tr>
<td>Telescope</td>
<td>156</td>
<td>256</td>
<td>291</td>
<td>307</td>
<td>323</td>
</tr>
<tr>
<td>Detector and optics</td>
<td>156</td>
<td>256</td>
<td>290</td>
<td>306</td>
<td>322</td>
</tr>
<tr>
<td>Servo</td>
<td>125</td>
<td>263</td>
<td>312</td>
<td>330</td>
<td>340</td>
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</table>
### Table 3-9 CTS IG Vibration Stresses

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>LOCATION</th>
<th>MAXIMUM STRESS, PSI</th>
<th>SAFETY FACTOR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRES A-286</td>
<td>SCAN SHAFT</td>
<td>9880</td>
<td>3.04</td>
</tr>
<tr>
<td>ALUMINUM</td>
<td>B.B. FRAME</td>
<td>5030</td>
<td>3.78</td>
</tr>
</tbody>
</table>

(* = VS MICROYIELD STRESS, CTS OPERATING IN SCAN LOCK)

### CTS Spin Effects (No Vibration Loads)

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>LOCATION</th>
<th>MAXIMUM STRESS, PSI</th>
<th>MIRROR TILT, °</th>
<th>SAFETY FACTOR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRES A-286</td>
<td>SCAN SHAFT</td>
<td>288</td>
<td>8.49</td>
<td>104.2</td>
</tr>
</tbody>
</table>

(* = VS MICROYIELD STRESS)
design margins exist to insure undegraded performance. Natural frequencies of various components were also calculated so that excessively large resonances could be eliminated. Tables 3-10 and 3-11 give results of these calculations and also list frequencies which were attenuated during vibration testing.

3.4 ELECTRONIC DESIGN

Figure 3-29 is a block diagram of the CTS electronics. The scene radiance, scanned by a rotating mirror, is modulated by a chopper blade and viewed by two (Hg,Cd)Te detector and one silicon detector. Three preamplifiers provide sufficient gain so that the video signals can be efficiently transmitted to post processing electronics located in the electronics assembly. Here video processors synchronously demodulate each signal, filter it through a low-pass filter and format the video and housekeeping information for output to video recorders. Also included in the electronics assembly are power supplies, chopper and scan motor control electronics, and housekeeping buffer electronics.

3.4.1 Video Format

In Figure 3-30 is a video timing diagram as a function of scan angle. The composite video line consists of 120 degree active scan video. This is the time during which scene is viewed. Following are five levels of electronic calibration signal, each 3.6 degrees wide. Ten housekeeping signals described in the following paragraphs occur immediately after the electronics calibration signals. During the last 120 degrees of each scan line both blackbody calibration signals are displayed. Also in the portion of the scan is included a provision for visual calibration, although no visual source has actually been incorporated in the scanner.

The video sync line and video gates are signals generated directly by the encoder and are accessible by way of a test connector in the bench checkout unit.

A listing of housekeeping signals included within each scan line of composite video is given in Table 3-12. Analog signals listed in the same figure are available as individual outputs and can each be monitored.
<table>
<thead>
<tr>
<th>MODE</th>
<th>FREQ, Hz</th>
<th>PARTICIPATION FACTORS</th>
<th>GENERALIZED WEIGHT</th>
<th>MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X1</td>
<td>X2</td>
<td>X3</td>
</tr>
<tr>
<td>1</td>
<td>149.7</td>
<td>-0.002</td>
<td>0.007</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>162.0</td>
<td>-0.085</td>
<td>0.90</td>
<td>-0.013</td>
</tr>
<tr>
<td>3</td>
<td>233.1</td>
<td>-0.17</td>
<td>1.11</td>
<td>0.51</td>
</tr>
<tr>
<td>4</td>
<td>285.3</td>
<td>-0.23</td>
<td>0.85</td>
<td>-0.71</td>
</tr>
<tr>
<td>5</td>
<td>362.6</td>
<td>1.33</td>
<td>1.60</td>
<td>-0.001</td>
</tr>
<tr>
<td>6</td>
<td>376.3</td>
<td>0.046</td>
<td>-0.026</td>
<td>1.47</td>
</tr>
<tr>
<td>7</td>
<td>410.6</td>
<td>-0.22</td>
<td>0.18</td>
<td>0.27</td>
</tr>
<tr>
<td>8</td>
<td>467.8</td>
<td>-0.92</td>
<td>0.26</td>
<td>-0.17</td>
</tr>
<tr>
<td>9</td>
<td>504.9</td>
<td>-1.0</td>
<td>0.077</td>
<td>0.10</td>
</tr>
<tr>
<td>10</td>
<td>561.1</td>
<td>0.73</td>
<td>0.33</td>
<td>-0.33</td>
</tr>
</tbody>
</table>
### Table 3-11 CTS 1G VIBRATION DEFORMATIONS

CTS OPERATING IN SCAN LOCK

<table>
<thead>
<tr>
<th>OPTICAL COMPONENT</th>
<th>OPTICAL BUDGET</th>
<th>VIBRATION DEFORMATION</th>
<th>MIN. SAFETY FACTOR *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>F = 149.7 Hz</strong></td>
<td><strong>F = 162 Hz</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>EXCITATION DIRECTION</strong></td>
<td><strong>EXCITATION DIRECTION</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>X1</strong></td>
<td><strong>X2</strong></td>
</tr>
<tr>
<td>SCAN MIRROR DECENTER, X2</td>
<td>--</td>
<td>0.21 mils</td>
<td>2.23 mils</td>
</tr>
<tr>
<td>SCAN MIRROR DECENTER, X3</td>
<td>--</td>
<td>0.00 mils</td>
<td>0.02 mils</td>
</tr>
<tr>
<td>SCAN MIRROR TILT, ( \theta \text{X2} )</td>
<td>30.9 ( \frac{\text{degs}}{} )</td>
<td>0.00 ( \frac{\text{degs}}{} )</td>
<td>0.27 ( \frac{\text{degs}}{} )</td>
</tr>
<tr>
<td>SCAN MIRROR TILT, ( \theta \text{X3} )</td>
<td>30.9 ( \frac{\text{degs}}{} )</td>
<td>6.7 ( \frac{\text{degs}}{} )</td>
<td>78.8 ( \frac{\text{degs}}{} )</td>
</tr>
<tr>
<td>SEC. MIRROR TILT, ( \theta \text{X2} )</td>
<td>180 ( \frac{\text{degs}}{} )</td>
<td>0.04 ( \frac{\text{degs}}{} )</td>
<td>0.10 ( \frac{\text{degs}}{} )</td>
</tr>
<tr>
<td>SEC. MIRROR TILT, ( \theta \text{X3} )</td>
<td>180 ( \frac{\text{degs}}{} )</td>
<td>0.19 ( \frac{\text{degs}}{} )</td>
<td>0.78 ( \frac{\text{degs}}{} )</td>
</tr>
<tr>
<td>SCAN MIRROR FIGURE</td>
<td>3 ( \lambda )</td>
<td>5.8 ( \lambda )</td>
<td>20.8 ( \lambda )</td>
</tr>
</tbody>
</table>

(*SAFETY FACTOR 1.0 INDICATES UNACCEPTABLE PERFORMANCE)

**SUGGESTED VIBRATION SPEC**

- 10-120 Hz: 1g
- 120-180 Hz: 0.2g (PREFER ELIMINATE 120-180 Hz)
- 180-2000 Hz: 1g
Figure 3-30 Video CTS Timing Diagram

- Scan Range
- Cold BB
- Hot BB
- Vis Cal
- Composite Video
- Marker
- Video Sync
- Video Gate
- Active Scan
- Housekeeping
- Cal Sources and Markers

Scan angles: 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°, 360°, 390°.
<table>
<thead>
<tr>
<th>COMPOSITE VIDEO</th>
<th>ANALOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>• HOT BLACKBODY TEMPERATURE (3)</td>
<td>• HOT BLACKBODY TEMPERATURE (5)</td>
</tr>
<tr>
<td>• COLD BLACKBODY TEMPERATURE (3)</td>
<td>• COLD BLACKBODY TEMPERATURE (5)</td>
</tr>
<tr>
<td>• TELESCOPE TEMPERATURE (1)</td>
<td>• TELESCOPE TEMPERATURE (1)</td>
</tr>
<tr>
<td>• RELAY OPTICS TEMPERATURE (1)</td>
<td>• CHOPPER TEMPERATURE (1)</td>
</tr>
<tr>
<td>• CHOPPER TEMPERATURE (1)</td>
<td>• RELAY OPTICS TEMPERATURE (1)</td>
</tr>
<tr>
<td></td>
<td>• HCT DETECTOR TEMPERATURE (2)</td>
</tr>
</tbody>
</table>
3.4.2 **Scan and Chopper Motors**

Table 3-13 is a summary of motor parameters for the scanner and chopper.

Figure 3-31 shows a block diagram of the motor control servo system for the scanning mirror assembly. The design employs a brushless dc motor controlled by a phase-locked loop (PLL). Past studies (and recommendations of NASA specialists) have shown that the use of a brushless dc motor is preferable especially when a synchronous gearless scanning system is required to meet tight short-term scan stability when operating in an adverse environment. An encoder provides the phase timing. The motor electronics logic contains a frequency reference, countdown logic, and a phase detector for the PLL. The encoder provides commutation signals for the master drive amplifier. The spin motor analog control converts the phase detector logic signals to an analog voltage and provides the frequency compensation for the PLL.

The encoder has five tracks: an incremental phase sensing track for the PLL, two tracks to provide commutation signals for the motor and two remaining tracks to synchronize the operation of the instrument data format.

A line to line stability of 25μs has been achieved in the CTS design.

3.4.3 **Power Switching and Operational Modes**

A power switching diagram showing distribution of power from aircraft power is given in Figure 3-32. All power distribution is done within the electronics box.

There are three operational modes of the CTS system:

1. Test
2. Flight
3. Descent

In the test mode all functions of the scanner are operational except that the calibration sources are not activated.
### Table 3-13 CTS MOTOR INFORMATION

#### SCAN MOTOR
- **TYPE**: BRUSHLESS DC MOTOR
- **COMMUTATION METHOD**: HALL SENSORS
- **OPERATING SPEED**: 2 REV/s
- **TORQUE SENSITIVITY**: 6.4 oz-in./amp
- **BACK EMF**: 45 mV/rad/s

#### CHOPPER MOTOR
- **TYPE**: INDUCTION MOTOR
- **NO. OF POLES**: 4
- **FULL LOAD SPEED**: 9200 REV/min
- **FULL LOAD TORQUE**: 5 oz-in.
- **EXCITATION VOLTAGE**: 115 V$_{\text{rms}}$
- **EXCITATION FREQUENCY**: 340 Hz
Figure 3-31 Block Diagram of Spin Motor Control
The flight mode is the full operational configuration of the system, while in the descent mode, all system functions are off except for the heating blankets. During descent, the heating blankets are switched on for condensation protection. Power status of the three modes is given in Table 3-14.

3.4.4 Schematics

The final circuits configuration can be found in up to date schematics delivered separately and listed in Appendix C.
<table>
<thead>
<tr>
<th>MODE</th>
<th>TEST</th>
<th>FLIGHT</th>
<th>DESCENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTS 28V POWER</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>CTS 115V POWER</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>EOI 115V, POWER</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
</tr>
</tbody>
</table>
SECTION 4
SYSTEM TESTS

This section gives results of tests performed at various levels of assembly.

All test results are given either in tabular or graphical formats.

4.1 IN-PROCESS TESTS

Results of tests performed on piece parts or sub-assemblies prior to system integration are given in this section.

4.1.1 Scanner Shaft and Bearings

a) Total Indicated Runout \( \leq 150 \times 10^{-6} \) inches
b) Bearing Torque Variation (Rough Spots) = 3.7 oz - inches

4.1.2 Chopper Jitter

a) Jitter = \( \pm 0.5 \mu s \) per revolution
b) Demodulation error (\( \phi_e \)) due to jitter:

\[
\phi_e = \pm 0.025\%
\]

4.1.3 Telescope Image Quality

See Figures 4-1 through 4-7. These traces were taken with a scanning slit microscope at various stages of system assembly.
4/30/76
Vertical Trace
Before Pinning

90% blur = \frac{0.00225}{24} - \frac{0.004}{96}

= 0.09375 - 0.0417 \text{ mrad}

90% blur = 0.052 \text{ mrad}
3 Same as 2 5/3/76
Except Photometer set on time
Constant = Slow
Pinhole Angular Size = .043 mrad
90% blur = .0154 - .043
= .062 mrad

Horizontal Trace

50%

90%

.00092" 0.04213
or .0383 mrad 0.1054 mrad

Figure 4-3
5/3/76
Horizontal Trace
After etching
.004" Filtrate diam.

Figure 4-5

90°
Figure 4-6

2 5/7/76
Vertical
.004" Pinhole after Heaters Installed

Background

.005"
4.1.4 Detector Spatial Response

Figures 4-8 and 4-9 are plots of channel 2 detector spatial response. This data was taken by measuring the signal from a pinhole/chopper combination located at the focal plane of a collimating mirror.

4.1.5 Spectral Response

Figures 4-10 through 4-12 are relative transmittance curves for each of the three spectral filters. Figures 4-13 and 4-14 are relative spectral response curves for the two HCT detectors.

4.1.6 Scan Speed Stability

Line to line jitter due to scan motor and drive electronics instabilities and bearing rough spots was measured. The maximum allowable jitter is 50 µs. The measured jitter is less than 25 µs.

4.2 VIBRATION TESTS

Vibration testing was performed at the Acton Environmental Testing Corporation. A complete test report is included in Appendix D. Prior to testing of the CTS units, a vibration survey was performed on the test fixture alone to determine its resonant frequencies. Vibration levels at these frequencies were then attenuated by the proper factors during CTS system tests.
Figure 4-11
Figure 4-12

E.A.S. 7/15/76
Channel 3 Filter Relative Spectral Transmittance
Max. Response = .828
Channel 2 Detector
Relative Spectral Response
D-Star Max. = 3.38 E 10

Figure 4-13
Figure 4.14

Relative Response

Wavelength (Micrometers)

1.00  0.80  0.60  0.40  0.20

0.00  2.00  4.00  6.00  8.00  10.00  12.00  14.00  16.00

7804-5
APPENDIX A
COOLER INSTRUCTION SHEETS
INSTRUCTION SHEET

MODEL 916AS COOLER
MODEL 916AS OPERATION

PROCEDURE

The model 916AS is a special recirculating cooler manufactured by Electro Optical Industries, Inc. It is designed for airborne use, and is powered from 115 VAC, 400Hz. No periodic maintenance is required. If a failure occurs, drawings useful for repair information are supplied.

The model 916AS is a recirculating heat exchanger useful in water cooling a remote heat source. Heat is removed with a recirculating fluid. The fluid is cooled in turn by passing through a small radiator. A small fan is included in the assembly to maintain air circulation through the radiator fins.

Do this to fill and operate:

1. Open hinged lid on cooler by removing screws.
2. Remove radiator tank cap and fill with water.
3. To turn on cooler - set switch to "on" position.
4. Observe water flow through plastic tubing.
5. If water does not flow through system - tip cooler towards pump side for priming.
6. Replace radiator cap and close lid cover.

(1)
LIST OF DRAWINGS:

100-842-5 NC  Wiring Diagram
100-842 NC  Assembly (sheet 1 of 2)
100-842 NC  Assembly (sheet 2 of 2)
1.0 SCOPE

This drawing describes the requirements and functions of an Optical Shaft Encoder used in conjunction with the Scan Mirror Assembly of the Cloud Top Scanner. The primary function of the encoder is to provide frame synchronization corresponding to the start of the scan period, calibration source synchronization and an incremental tachometer output.

2.0 TECHNICAL REQUIREMENTS

2.1 Function

- The function of the encoder is to provide the following outputs:

  a) A once per revolution frame synchronization pulse is required corresponding to the start of the data taking scan period.

  b) Active scan and calibration source synchronization pulses are required to identify the location of the active scan period and each of three calibration sources.

  c) A tachometer output is required to provide verification of scan wheel rotational rate.

The position at which each of the output pulses occurs is given in the "Encoder Timing Diagram" shown on sheet 1.
2.2 Mechanical Characteristics

2.2.1 Physical Configuration - The encoder shall consist of a Housing Assembly containing the Code Disc Readout Assembly and associated electronics and a code disc. The code disc shall be attached to an HRC furnished disc mounting flange. The Encoder Housing shall be as specified on Sheet 1.

2.2.2 Weight - The weight of the encoder shall not exceed TBD ounces.

2.3 Electrical Characteristics

2.3.1 The power required for the lamps and encoder electronics shall not exceed the following:

Lamps +5VDC ± 5% < TBD watts
Electronics +5VDC ± 5% < TBD watts

2.3.2 Electrical Interface

2.3.2.1 Isolation - All signal and power leads shall be isolated from the encoder housing. The lamp power shall be isolated from the electronic power.
2.3 Installations: All connections shall be brought as specified in wiring diagram, Sheet 1. color and size to be as noted. Wire to MIL-W-16873/4 Type E. Tag wire ends and mark functions (i.e., "SCAN A", "SCAN B" etc.) Lead length outside case to be 24.0 inches min.

2.3.3 Output Characteristics - Each output waveform shall exhibit the following pulse characteristics under the following conditions:

a) Operating temperature per 2.3.4
b) Total shaft runout TBD
c) Random variation in shaft runout TBD
d) Axial motion of shaft TBD
e) Operating speed 120 RPM unidirectional

Items (b) through (e) above relate to interface conditions associated with direct mounting to HRC structure and shaft as shown on Sheet 1.

2.3.3.1 Amplitude - All outputs differential via transmittor line driver. Pulse present will follow positive true convention.

Voltage Level (pos) > 2.4 VDC
Voltage Level (neg) < 0.7 VDC
Leading Edge < 400 ns
Trailing Edge < 400 ns
Pulse Width See Figure 1
2.3.3.2 Accuracy - Absolute position accuracy of all pulse transitions ≤30 sec.

2.3.4 Environment:

Operating Temperature Range -40°C to +40°C
Non-Operating Temperature Range -40°C to +40°C

Altitude-Operating - Sea Level to 70,000 Ft.
Vibration-Operating - 1G at 20 to 2,000 Hz
APPENDIX C

DRAWING LIST
<table>
<thead>
<tr>
<th>REV</th>
<th>ASY LEVEL</th>
<th>DWG. NO.</th>
<th>REF. DESIG.</th>
<th>TITLE</th>
</tr>
</thead>
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<td>67</td>
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<td>YK45A1</td>
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<td>INSTALLATION DWG CTS SYSTEM</td>
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<td>YK45A1</td>
<td></td>
<td>INSTALLATION DWG CTS TEST EQUIP</td>
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<td>67</td>
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<td>21012055 D</td>
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<td>SCHEMATIC, PWR INPUT SWITCHING</td>
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<td>4</td>
<td>21014064 D</td>
<td></td>
<td>TEST CABLES W1, N2, W3, W4, W5, W6, W7, W8</td>
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<td>67</td>
<td>5</td>
<td>21016947 D</td>
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<td>SYSTEM INTERCONNECT DIAG TEST</td>
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<td>6</td>
<td>21016948 D</td>
<td></td>
<td>SYSTEM INTERCONNECT DIAG FLIGHT</td>
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**Title:** Board Assy. Charger Control

**Diagram:** Board Blank

**Legend:**
- Board Blank
- Board Assy. Charger Control
- Board Assy. Switch
- Chart

**Note:** Board Assy. Switch contains a series of symbols and numbers.
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Report of Test on VIBRATION TESTING OF CLOUD TOP SCANNER FOR HONEYWELL, INC. UNDER PURCHASE ORDER NO. BX96376

Date February 4, 1977

Prepared Checked Approved
By A. LeBourdais M. Casaubon M. L. Tolf
Signed M. Casaubon M. L. Tolf
Date 2/4/77 2/4/77 2/4/77
MLT: AWL/hmf
Administrative Data

1.0 Purpose of Test: To subject Cloud Top Scanner and Cloud Top Scanner fixture to vibration testing and evaluation.

2.0 Manufacturer:

   Honeywell, Inc.

3.0 Manufacturer's Type or Model No: Item identified as Cloud Top Scanner.

4.0 Drawing, Specification or Exhibit:

   Per Honeywell, Inc. representative's instructions. (See requirements and procedures herein).

5.0 Quantity of Items Tested:

   One (1)

6.0 Security Classification of Items:

   Unclassified

7.0 Date Test Completed:

   January 28, 1977

8.0 Test Conducted By:

   D. McLaughlin

9.0 Disposition of Specimens:

   Returned to Honeywell, Inc.

10.0 Abstract:

   Evaluation of the fixture and scanner was made by Honeywell, Inc. representative.

Report No. 12997

Page 1
1.0 REQUIREMENTS

The Cloud Top Scanner test fixture with dummy load shall be subjected to a sinusoidal survey. Following this sinusoidal survey, the Cloud Top Scanner shall be subjected to sinusoidal vibration exposures in the vertical and longitudinal axes. These tests are as detailed in procedures herein.

2.0 PROCEDURES

Per Honeywell, Inc. representative's instructions, 12-accelerometers, 2-visicorders and a magnetic tape system were utilized for this vibration test program.

The following test program was performed under the direction of Honeywell, Inc. representative:

TEST NO. 1

The fixture was secured for vibration testing in the vertical axis. A dummy load supplied by Acton Environmental Testing Corporation(AETC) was secured to the test fixture. Six accelerometers were attached and were recorded, utilizing a Minneapolis-Honeywell Visicorder. The test fixture/dummy load configuration was then subjected to a sinusoidal vibration test from 20-2000 Hz at a 1g level and at a sweep rate of 2 octaves/minute. Following this survey in the vertical axis, Test No. 2 was performed.

TEST NO. 2

Vertical axis - Cloud Top Scanner attached to test fixture. 12-accelerometers were utilized and the 2-visicorders and the magnetic taping system was utilized. The following test was performed:

- 20-120 Hz @ 1g
- 120-180 Hz @ .2g
- 180-850 Hz @ 1g
- 850-1050 Hz @ .5g
- 1050-2000 Hz @ 1g

Report No. 12997
Sweep rate during test was at 2 octaves/minute

Following Test No. 2, direction of vibration was changed to longitudinal and Test No. 3 was performed.

TEST NO. 3

Longitudinal axis - test fixture and dummy load. Six accelerometers and a visicorder were utilized for this test. Test was from 20 to 2000 Hz at a 1g level and at a sweep rate of 2 octaves/minute. Following this test, the Cloud Top Scanner was mounted to the test fixture and Test No. 4 was performed.

TEST NO. 4

Longitudinal axis - Cloud Top Scanner. Twelve accelerometers were utilized, 2-visicorders and a magnetic tape system. The following test was performed:

- 20 - 120 Hz @ 1g
- 120-180 Hz @ .3g
- 180-340 Hz @ 1g
- 340-480 Hz @ .5g
- 480-2000 Hz @ 1g

Sweep rate during test was at 2 octaves/minute.

NOTE: DURING THE FIRST RUN OF TEST NO. 4, THE VIBRATION AMPLIFIER DROPPED OUT AT 50 Hz. TEST WAS STOPPED AND TEST NO. 4 WAS RE-STARTED FROM THE 20 Hz FREQUENCY.

During vibration testing of the Cloud Top Scanner, the Cloud Top Scanner was operated and monitored by Honeywell, Inc. representatives. All visicorder recordings generated during vibration testing were retained by Honeywell, Inc. representatives. The magnetic tape recordings of Runs #2 and 4 were analyzed by Acton Environmental Testing Corporation and are included with this report.
3.0 RESULTS

Evaluation of the test fixture and Cloud Top Scanner during and after vibration exposures was performed by Honeywell, Inc. representatives.
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<tr>
<th>NAME</th>
<th>MFGR.</th>
<th>MODEL</th>
<th>SER.NO.</th>
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<td>42167</td>
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