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BACKSCATTER HAZE DEVICE FOR MEASUREMENT OF HAZE IN AIRCRAFT TRANSPARENCIES (U)

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NOTICES

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

KENNETH R. BOFF, Chief
Human Engineering Division
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The method currently used throughout the aircraft transparency industry to measure haze is ASTM Test Method D1003. This procedure was originally developed for applications involving small, thin, and flat transparent parts. Major limitations of Test Method D1003 include its restriction to small, flat samples and its requirement for having the source and detector on opposite sides of the sample under test. In order to facilitate field testing of installed aircraft windscreens, a test method was developed which overcomes the limitations of Test Method D1003. The new method determines haze values by measuring the amount of light backscattered off the surface of the transparency under test. A prototype instrument was developed and tested against D1003. The results of those tests are presented. The new instrument consists of an integrating sphere, a mechanically chopped incandescent light source, a silicon detector, and supporting electronics. This report describes the device, which is based on US Patent Number 4,687,338, in detail. Use of this type of device in the field could provide quantitative data for determining when an installed aircraft windscreen should be replaced or refinished in place.

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Summary

Halation is the scattering of light out of a beam while it transits nominally transparent parts. It is an important optical parameter for aircraft transparencies since the amount of halation can severely affect out-of-cockpit visual acuity.

The method currently used throughout the aircraft transparency industry to measure haze is ASTM Test Method D1003. This procedure was originally developed for applications involving small, thin, and flat transparent parts. Major limitations of Test Method D1003 include its restriction to small, flat samples and its requirement for having the source and detector on opposite sides of the sample under test. In order to facilitate field testing of installed aircraft windscreens, a test method was developed which overcomes the limitations of Test Method D1003. The new method determines haze values by measuring the amount of light backscattered off the surface of the transparency under test. A prototype instrument was developed and tested against D1003. The results of those tests are presented. The new instrument consists of an integrating sphere, a mechanically chopped incandescent light source, a silicon detector, and supporting electronics. The device is described in detail. This device is based on US Patent Number 4,687,338. Use of this type of device in the field could provide quantitative data for determining when an installed aircraft windscreen should be replaced or refinished in place.

Preface

This report was prepared under work unit 7184-18-02 by members of the Visual Display Systems Branch, Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio. Funding was provided by the Wright Research and Development Center's Aircrew Protection Branch (WRDC/FIVR).

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Introduction

The accepted method of measuring haze is based on a technique developed by the National Institute of Technology and Standards (NITS), formerly the National Bureau of Standards. This method has been adopted by the American Society for Testing and Materials (ASTM) and the Federal Government [17]. ASTM Test Method D1003 describes this accepted procedure for measuring haze in transparent materials. The basic procedure consists of directing a collimated beam of light through the material under test and measuring the total transmitted (undeviated) and forward scattered light using an integrating sphere [6]. The apparatus is illustrated in Figure 1.1 [19]. This procedure requires that the light source and detector be on opposite sides of the sample under test. The procedure described in D1003 is adequate for laboratory measurements of relatively small test coupons. However, it is difficult to apply the procedure to the measurement of large samples, such as aircraft windscreens. The necessity of having the light source and detector on opposite sides of the transparency under test presents particularly acute problems for field measurements of installed aircraft windscreens. This report describes a device and procedure which determines the haze value for transparent parts (such as aircraft windscreens, aircraft canopies, and sample coupons) through the measurement of backscattered light. This new device has the light source and detector located on the same side of the object, allowing it to easily make accurate field measurements. The haze values obtained with this instrument correlate well with those achieved using ASTM Test Method D1003. Use of this type of device in the field could provide quantitative data for determining when an installed aircraft windscreen should be replaced or refinished in place.

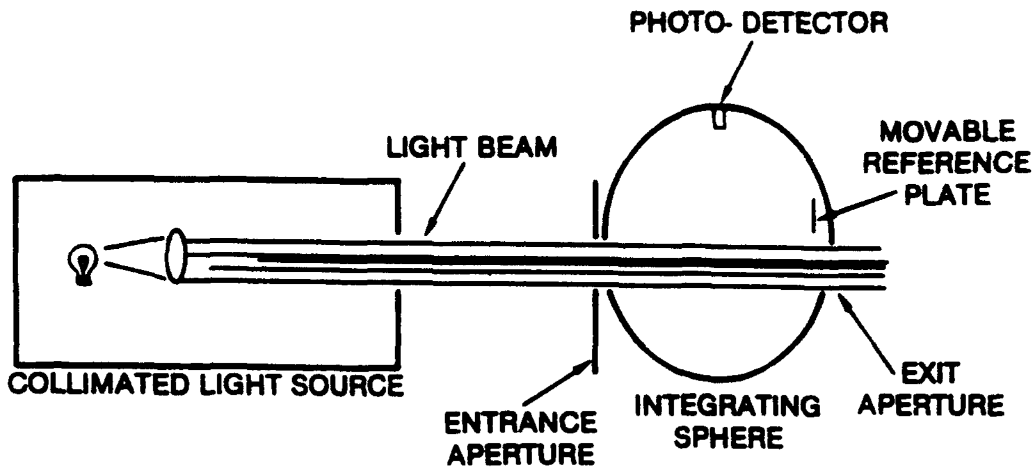


Figure 1.1: ASTM Test Method D1003 Apparatus

Method

2.1 Terminology

Haze is the spatial attribute of smokiness or dustiness that interferes with clear vision. It is defined as the ratio of diffuse to total transmittance for an incident beam [3]. It can also be characterized as the percentage of transmitted light which deviates from the incident beam due to forward scattering.

Backscatter is electromagnetic radiation (in this case visible light) that is diffracted from a surface toward the same side as the incident beam.

Forward scatter is electromagnetic radiation that is diffracted from a surface in the direction of the transmitted beam.

2.2 Theory of Operation

Based on the fundamental principal of energy conservation, light incident on a transparent material is either transmitted, specularly reflected, absorbed, backscattered, or forward scattered. Figure 2.1 illustrates this relationship. Only the transmitted light retains its image forming properties, therefore carrying useful information [17]. The forward scattered component produces haze. The transmitted component is sometimes referred to as the 'coherent' component, while the scattered component is referred to as 'incoherent' [5]. The National Institute of Technology and Standards definition of haze is the ratio of forward scattered light to the total light (both 'coherent' and 'incoherent') passed by the transparency [17]. In equation form:

$$H = \frac{S}{S+T} \tag{2.1}$$

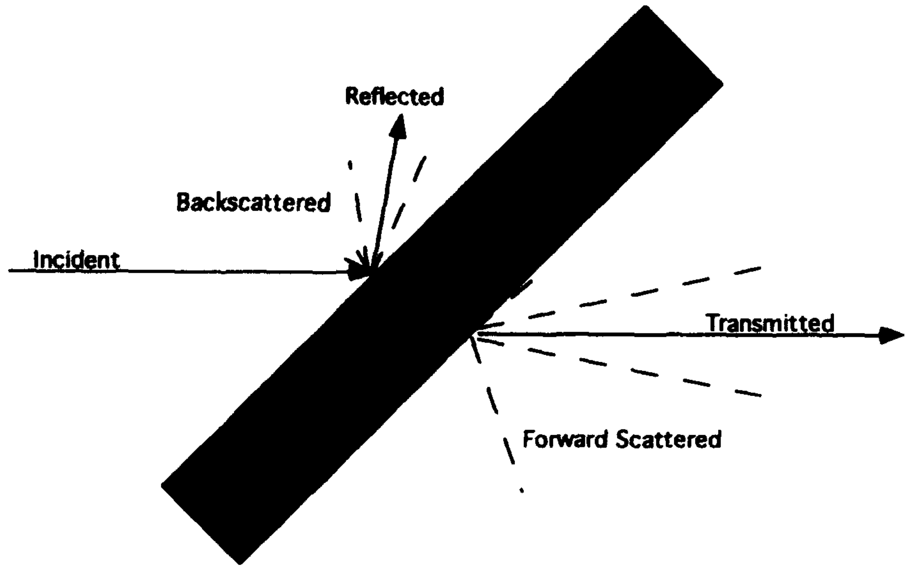


Figure 2.1: Disposition of Light Incident on a Transparent Material

where H is the haze value, S represents the forward scattered light, and T is the transmitted or image forming light.

Haze is produced by scattered light, which is a manifestation of the fundamental process of diffraction. This diffraction of the incident beam is caused by imperfections, either surface or bulk, in the transparency. There are four sources of forward and backscattered light in transparent parts[16]:

1. Scattering from surface topography,
2. Surface contamination,
3. Bulk refractive index variations, and
4. Bulk particulates.

Figure 2.2 illustrates these scattered light generating sources. Forward scattering is, in most cases, approximately two orders of magnitude (100X) greater than backscattering for transparent materials [16]. Concerning surface topography, a surface is considered optically rough (and therefore a scattering surface) if the following condition is met [4]:

$$h \geq \frac{\lambda}{8 sin\gamma} \tag{2.2}$$

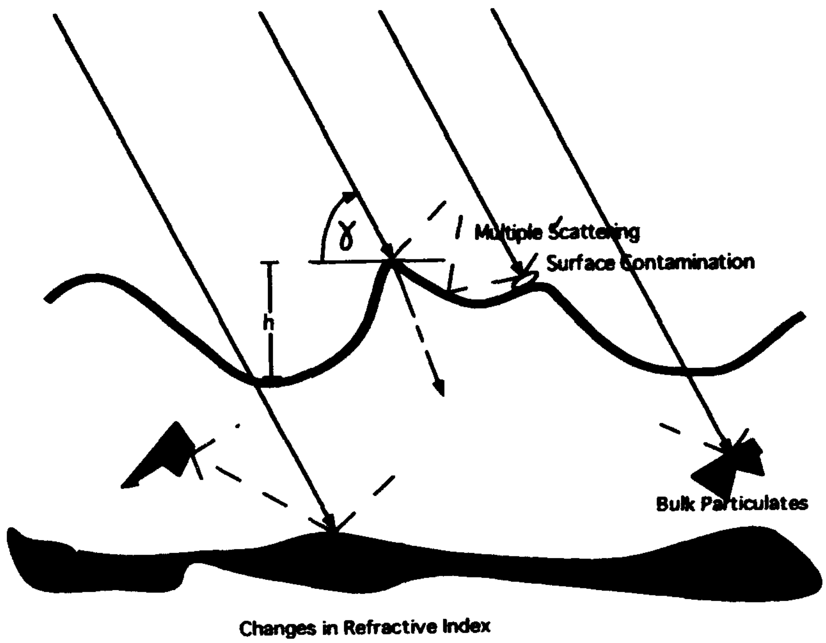


Figure 2.2: Sources of Scattering in Transparent Materials

where h is the height of surface features and γ is the angle of incidence. The sources of scattering in transparent materials and the relationship of h and γ to those sources are presented in Figure 2.2.

A basic assumption for a practical backscattered light measuring approach for haze determination is that most of the scattering associated with transparencies of interest is caused by surface defects. If this condition is met, the measurable backscattered component will be proportional to the forward scattered component. Previously published data support this assumption in principle [16, p.96]. For a transparency with a refractive index of 1.5 (n=1.5) and an optically smooth surface, Fresnel's Law of Reflection [11]:

$$R = \frac{(n-1)^2}{(n+1)^2} \tag{2.3}$$

indicates 4% of the energy in a normally incident beam at the air-material interface will be specularly reflected [9]. Surface imperfections will produce backscattering, increasing the total amount of energy returned to the incident side of the transparency. Surface imperfections are classified as scratches or digs [13]. The specularly reflected beam, typically several orders of magnitude greater in intensity than the various diffracted orders, carries no information regarding surface quality and should not be measured.

Precise diffraction calculations are mathematically intensive, in many cases closed solutions do not exist [16]. When dealing with extended, optically rough surfaces the situation becomes even more complex due to the high probability of multiple scattering at the surface. However, a few reasonable assumptions allow development of insight into this environment. Assuming surface scratches are often due to cleaning processes [12], in many cases they approximate a sinusoidal grating. In a given area of any transparency, a number of such gratings of varying orientations and spatial frequencies may be superimposed on each other. Figure 2.3 illustrates such a set of scratches on the surface of a test coupon. The reticle in the photograph is ruled in 0.001 inch increments. The scratches on this sample represent an extreme case in terms of width and uniform orientation. The various angles of diffraction possible from such a grating are defined by the grating equation [7],

$$d sin\theta = m\lambda \tag{2.4}$$

where m is the order of diffraction and d is the grating spacing or, in this case, the distance between scratches. The intensity of light diffracted in any order is given by [5]:

$$I \sim (\frac{A}{\lambda})^{2|m|} \tag{2.5}$$

where A is the depth of the grating. In summary, the spectral distribution of incident electromagnetic energy and the spacing of surface scratches determine the angles of diffraction and depth of the scratches determines the actual power diffracted into any order. These are important quantities as they define how much haze will be observed with a given viewing geometry. Under operational conditions with the sun as the light source and transparencies on aircraft in flight as the test samples, there are innumerable possible viewing geometries. For a particular transparency, for some viewing geometries the observed haze will be significant while for others it may be negligible. Haze values increase as the angle of incidence increases [12]. Due to prevailing wind conditions, many runways in the United States are oriented NE-SW, with landings and takeoffs generally made to the southwest, the general direction of the setting sun for much of the year. At low sun elevations, the sun's angle of incidence is at a maximum for most canopies and this increased angle of incidence generally results in increased scattering [5]. Aircraft transparency haze is particularly a problem for aircrews under these conditions [18]. Ideally, it would be desirable to make haze measurements pertinent to the position of the pilot's eyes for a multitude of sun conditions. However, the method for measuring haze in ASTM D1003 measures *all* light forward scattered into a hemisphere out of a normally incident beam. Therefore, the backscatter device described here also provides for a normally incident sampling beam on the part under test. D1003 dictates use of a CIE Source C lamp, the output of which corresponds to the spectral distribution of sunlight, approximately a 6000 K blackbody. As noted above, scattering is wavelength dependent. The backscatter method developed here uses an incandescent source approximating a 2856 K blackbody. While exact

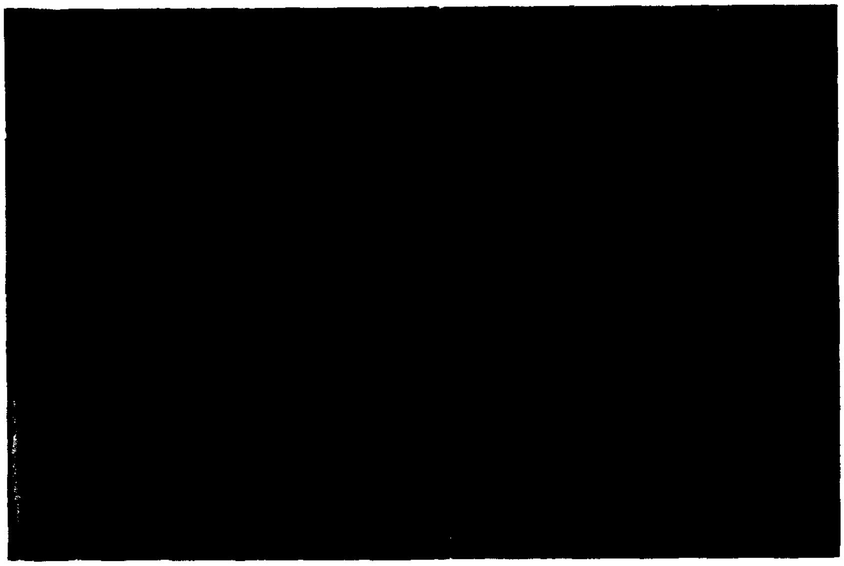


Figure 2.3: Distribution of Scratches on the Surface of an Aircraft Transparency. Reticle Increments = 0.001 inch.

wavelength scaling is generally not possible [14, 16], scattering in the visible resulting from use of a 2856 K source should approximate that produced by incident 6000 K energy.

2.3 Apparatus

Optical Design

This device is designed to measure the energy within the spectral distribution of the source backscattered from a transparent part, while ignoring specularly reflected light. The device consists primarily of a light source, an integrating sphere, a detector, driving electronics, and a display readout. The image of the filament is projected from one 1.5 inch diameter port of a six inch diameter integrating sphere. The sample under test is placed at the opposing 1.5 inch diameter port. The sampling beam diameter of the backscatter device is approximately 1/2 that of the XL-211 Hazeguard Hazemeter [15]. The photodiode is located at the third port, shielded from direct spurious reflections by a baffle. Each measurement is a spatial integration over an approximately cylindrical area of the test sample. Light specularly reflected off the sample is dissipated in a light trap and does not contribute to the measurement. The overall design and measurement geometry is depicted in Figure 2.7 on page 13.

A 12 volt, 12 watt incandescent bulb serves as the light source. The bulb's filament is positioned at the center of curvature of a small hemispherical mirror with a focal length of 6 mm. Use of the mirror increases overall device output 50%. The output of the bulb is collected with a F/1.0, 10 mm focal length condenser. The condenser lens assembly forms an image of the filament in the center of an oblong aperture, the dimensions of which approximate those of the filament, in the object space of the 50.2 mm focal length, F/2 image projection lens. The source is mechanically chopped at this point. The oblong aperture serves to block stray light from entering the integrating sphere. The position of the projection lens relative to the image of the filament can be varied, providing some degree of control over the size of the sampling area. Light baffles, item 4 in Figure 2.7, are used between the projection lens and the oblong aperture to further reduce stray light.

A major potential problem with an integrating sphere approach is inadvertently measuring specularly reflected energy from the curved surfaces of the transparencies under test. Based on data from reference [8], 16 inches is the greatest windscreen radius of curvature likely to be encountered. Based on an analysis of the geometry involved and the specifics of the backscatter device's design, all directly reflected light from surface radii likely to be encountered will be trapped by the baffles provided. Figure 2.4 illustrates the reflection geometry analyzed in this effort. Three rubber feet arranged in an equilateral triangle configuration around the measuring port provide the device the capability to sit squarely on surfaces with radii of curvature greater than 15 inches.

The backscatter device uses a United Detector Technology (now Graseby Optronics) silicon photovoltaic photodiode with a circular 1 cm^2 active area. The detector's output current is linear over seven decades of input power [10]. The peak spectral response of a silicon detector occurs near the maximum output of a 2856 K blackbody source, as depicted in Figure 2.5.

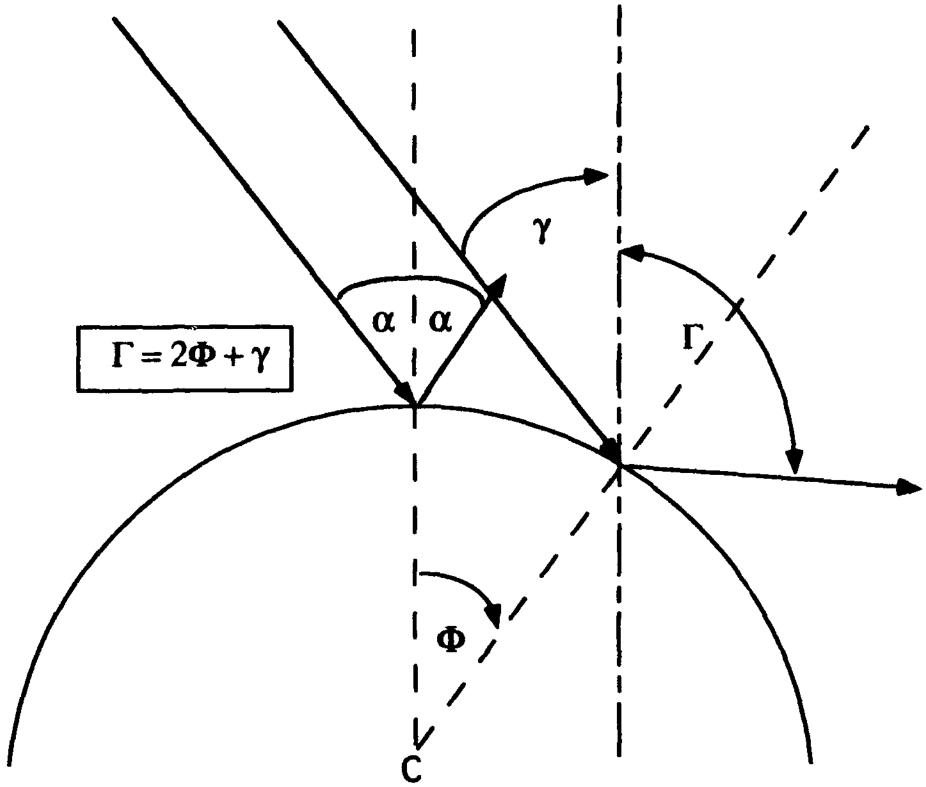


Figure 2.4: Reflection Geometry Involved with Curved Surfaces

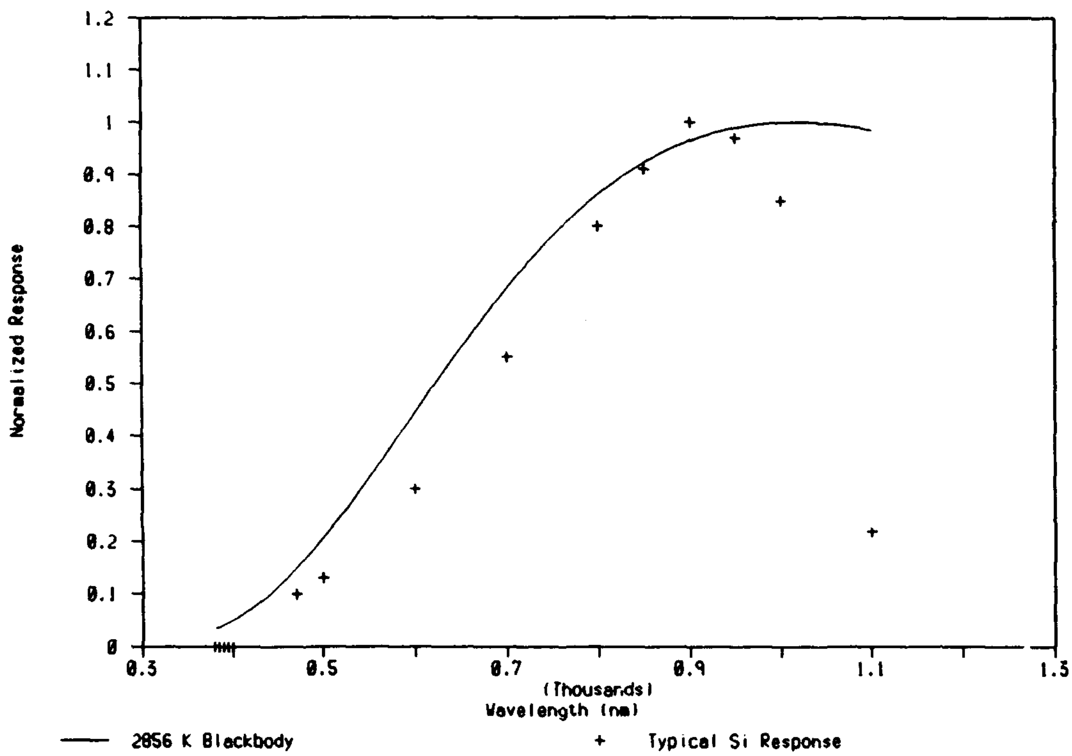


Figure 2.5: Comparison of a 2856 K Blackbody Spectral Output and the Spectral Response of a Silicon Detector

Electronic Design

The device electronics are composed of two main sections: power distribution and signal processing. The power distribution section generates the required voltage levels from the single 12 volt DC input voltage. The signal processing section conditions the backscattered light information into a usable voltage and displays this result on the front panel digital display. Schematic diagrams of the overall electronic design are included in Appendix A.

Power Distribution

The power distribution section consists of two subsections, the main power electronics and the light source electronics.

The main power electronics are driven by an external 12 volt, 1.5 amp minimum power source. The external power source can be any high current 12 volt source, such as a car battery or an AC to DC 12 volt converter. The main power electronics consist of a low drop out voltage regulator, a split power supply circuit, and a low voltage detection circuit. The low drop out voltage regulator drops the 12 volt input down to a regulated 10 volts. The split power supply then generates a floating ground reference to give the signal processing section the required +5 and -5 voltage levels. The low voltage detection circuit indicates two conditions by activating the far left decimal point in the digital output display: 1) failure of the main fuse and 2) input voltage less than 12 volts.

The light source electronics are comprised of the lamp control switch and the chopping motor voltage regulator. The lamp control switch is a front panel switch which activates the lamp, see Figure 2.8 on page 14. The chopping motor voltage regulator adjusts the motor's speed to maintain a constant chopping frequency, currently 1033 Hertz using an 18 period chopping wheel.

Signal Processing

The signal processing section consists of seven subsections:

1. a photodiode amplifier,
2. a bandpass filter,
3. a reference adjust amplifier,
4. a buffered rectifier,

5. a 2 stage low pass filter with zero offset adjustment,
6. a digital output display, and
7. the limit detection circuit.

The photodiode amplifier converts the backscattered light signal information contained in the output current of the photodiode to a voltage signal. This signal is then fed to the bandpass filter which uses an oscillator's frequency (divided by 100) to amplify and pass only the signal generated by the light source electronics. The signal level is calibrated by the reference adjust amplifier and passed to the buffered rectifier to obtain a positive full wave rectified signal. The rectified signal is filtered by the low pass filter section to remove frequency components above 1 Hertz. The zero adjustment provides the capability to zero a limited amount of ambient light from the backscattered signal. The processed backscatter information is then displayed on the front panel digital display. The limit detection circuit determines is too much light, whether ambient or specularly reflected, is present for the system to successfully account for. Such a condition is indicated by illumination of the middle decimal point in the digital display.

The backscatter device is actuated by a trigger on one of two externally mounted handles. The handles make the device easy to hold, position, and use. Overall weight is approximately six pounds. Figure 2.6 contains two views of the completed unit and Figures 2.7 and 2.8 are a cut away diagram and a top view of the device respectively.

2.4 Procedure

A flat sample of any type of transparency with a known haze value, as measured by ASTM D1003, can serve as the calibration reference. A 50 mm X 50 mm, 5 mm thick flat glass sample with a haze value of 16.5%, as measured by the XL-211, is used as the calibration reference for the prototype backscatter device.

After calibration, place the sampling aperture of the backscatter device on the section of the transparency to be tested. This is accomplished by centering the overall device over the area of interest. Press the trigger and read the display. If the display cannot be read easily due to inadequate ambient lighting, release the trigger before moving the device, this will hold the reading on the display. This reading is the haze value for the section of the transparency measured.

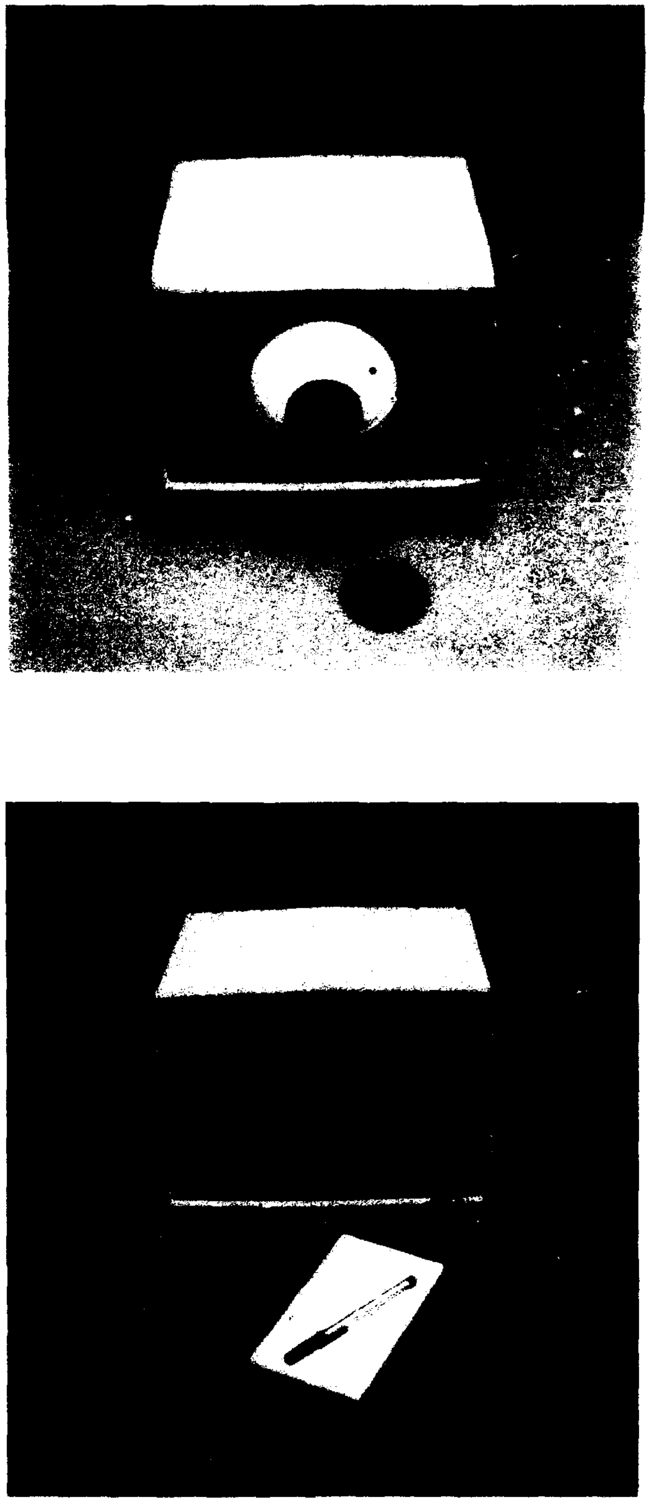
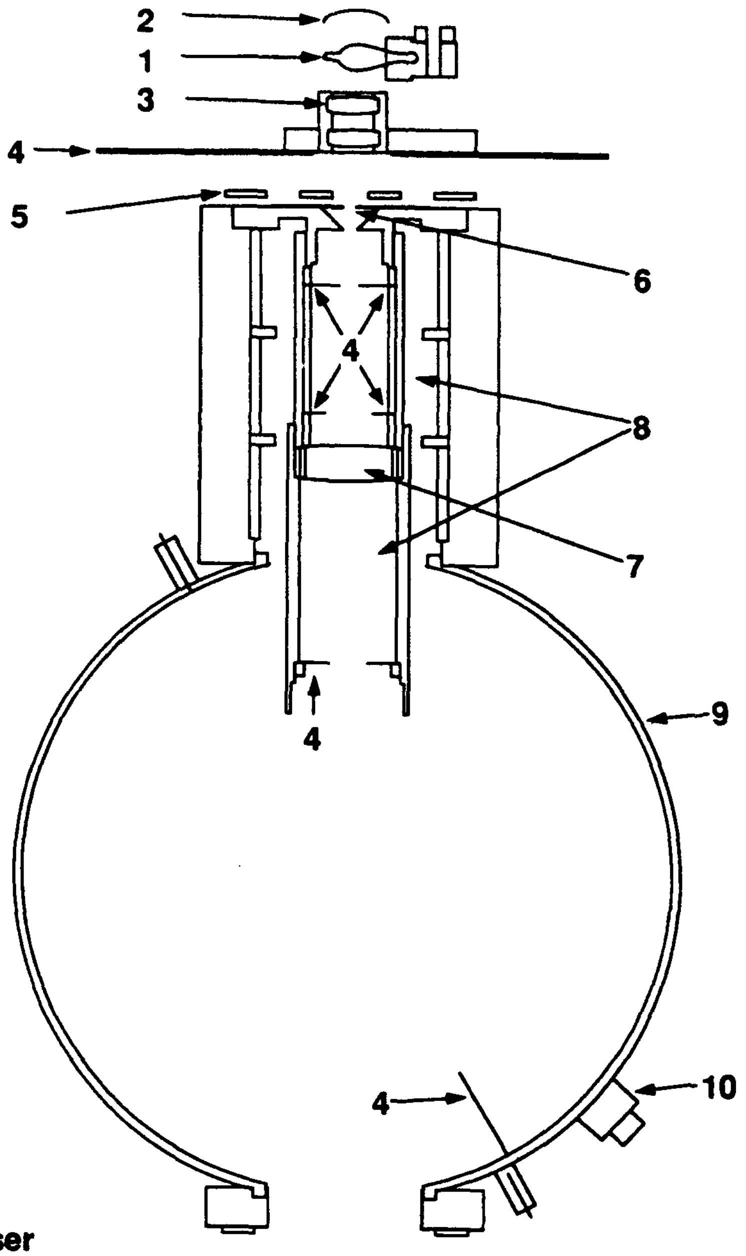


Figure 2.6: Two Views of the Backscatter Haze Device Prototype



1 Lamp
2 Mirror
3 Condenser
4 Baffles
5 Chopping Wheel
6 Limiting Aperture
7 Projecting Lens
8 Light Traps
9 Integrating Sphere
10 Detector

Figure 2.7: Cut Away Illustrating the Overall Design of the Backscatter Haze Device

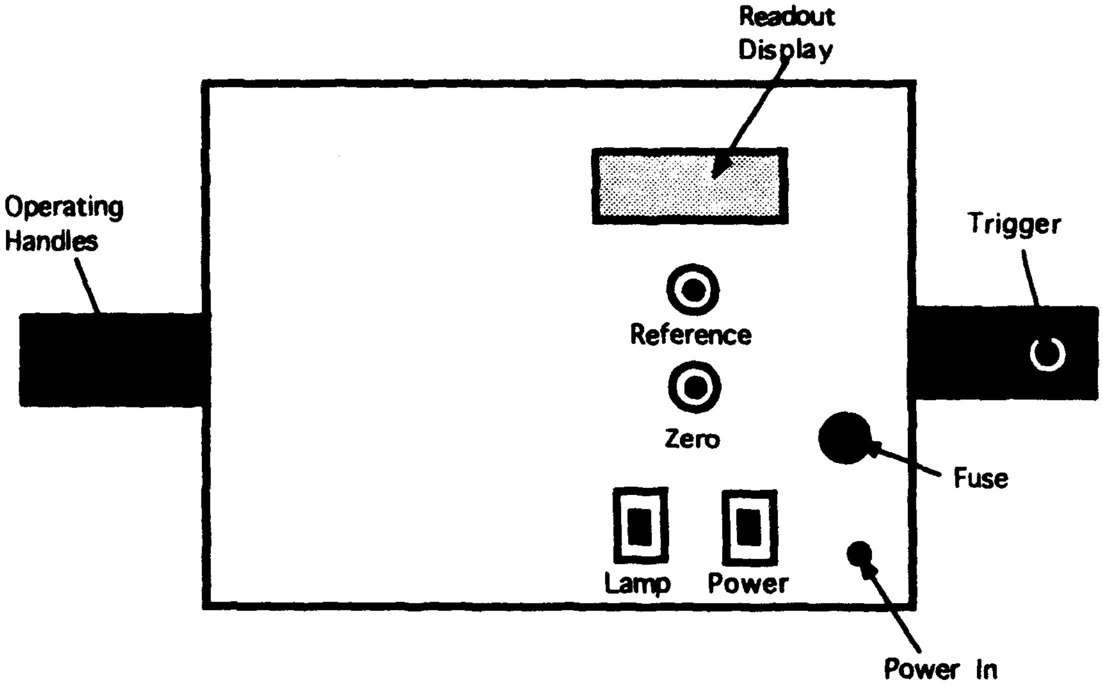


Figure 2.8: Top View of the Backscatter Device Depicting the Control Panel

Results

The accuracy and precision of the new backscatter device for measuring haze was determined through a series of indoor measurements of 11 transparent samples, one of which serves as a calibration sample, of varying haze values. All samples used in this initial testing were 5 mm thick plane parallel glass plates. The primary emphasis of this testing was to verify the validity of the backscatter approach. Maximum accuracy of the XL-211 derived haze values, necessary for accurate comparison with backscatter derived haze values, is achieved only when using plane parallel plate samples.

Laboratory evaluation of 10 test samples resulted in a correlation coefficient of r= 0.998 between the backscatter method and the ASTM D1003 method [20]. Figure 3.1 graphically depicts the correlation between the haze values obtained using the two methods. The haze values of the test samples ranged from approximately 0% to 16% as measured by the D1003 method. Samples were restricted to haze values below 30% because the manufacturer of the XL-211 does not guarantee the accuracy of that instrument for haze values greater than 30%. Table 3.1 summarizes the haze values obtained using the two methods. The values in table 3.1 are the mean values for five measurements for each method. The ASTM D1003 Test Method results were obtained using an XL-211 Hazeguard Hazemeter. Table 3.1 indicates the backscatter approach can, in most circumstances, return a haze value within 0.5 of the D1003 haze value. The displayed haze values in each case are percentages.

Table 3.2 summarizes the comparison of the precision of the two methods. The values in table 3.2 are the fractional standard deviations, obtained by dividing the standard deviation for each set of measurements by its mean value. These data indicate the precision of the two methods is comparable.

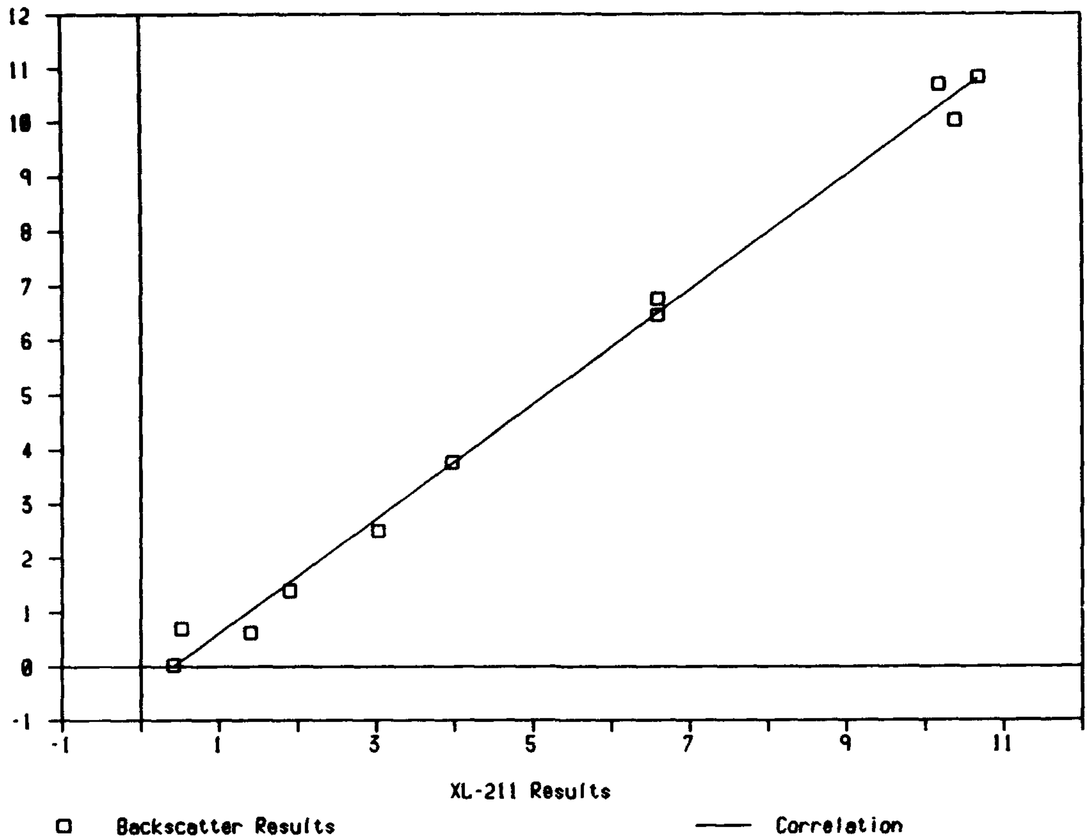


Figure 3.1: Correlation of D1003 and Backscatter Haze Results

Table 3.1: Comparison of Results using ASTM D1003 Methodology and the Backscatter Method

	Mean Haze Values (%)		
Sample	D1003 Method	Backscatter Method	$\mid \Delta DisplayedHazeValue \mid$
1	0.5	0.7	0.2 %
2	1.4	0.6	0.8 %
3	1.9	1.4	0.5 %
4	3.0	2.5	0.5 %
5	4.0	3.8	0.2 %
6	6.6	6.5	0.1 %
7	6.6	6.8	0.2 %
8	10.7	10.8	0.1 %
9	10.2	10.7	0.5 %
10	10.4	10.0	0.4 %
11	16.5	(Reference)	N/A

Table 3.2: Comparison of the Precision of the Two Methods

	$\frac{\sigma}{h}$	
Sample	D 1003 Method	Backscatter Method
1	0.08	0.11
2	0.0	0.074
3	0.0	0.0
4	0.14	0.0
5	0.11	0.125
6	0.0	0.007
7	0.0	0.007
8	0.0	0.004
9	0.0	0.0
10	0.0	0.005
11	0.0	(Reference)
Avg:	0.033	0.033

Discussion

Preliminary results obtained with the backscatter device prototype indicate potential for this method to successfully determine haze values of installed transparencies under certain conditions. The current version of the device suffers from several limitations, including:

1. Poor signal to noise ratio under high ambient lighting conditions, making it unreliable during measurements in direct sunlight, and
2. Very small angular positioning tolerances with respect to the local windscreen normal.

In an attempt to alleviate these deficiencies and improve effectiveness during field use, a prototype based on a transmissive mode of operation is currently being developed. This two piece transmissive version incorporates use of an electronically chopped eye safe laser light source emitting at 670 nm. The goals of using a laser diode light source include improved source brightness, extended battery operation, and the ability to visually verify proper alignment during measurements. Use of a transmissive mode of operation also eliminates the need to use a reference sample.

Possible future improvements include use of a smaller (4 inch diameter) integrating sphere to make the receiver more compact and easier to handle.

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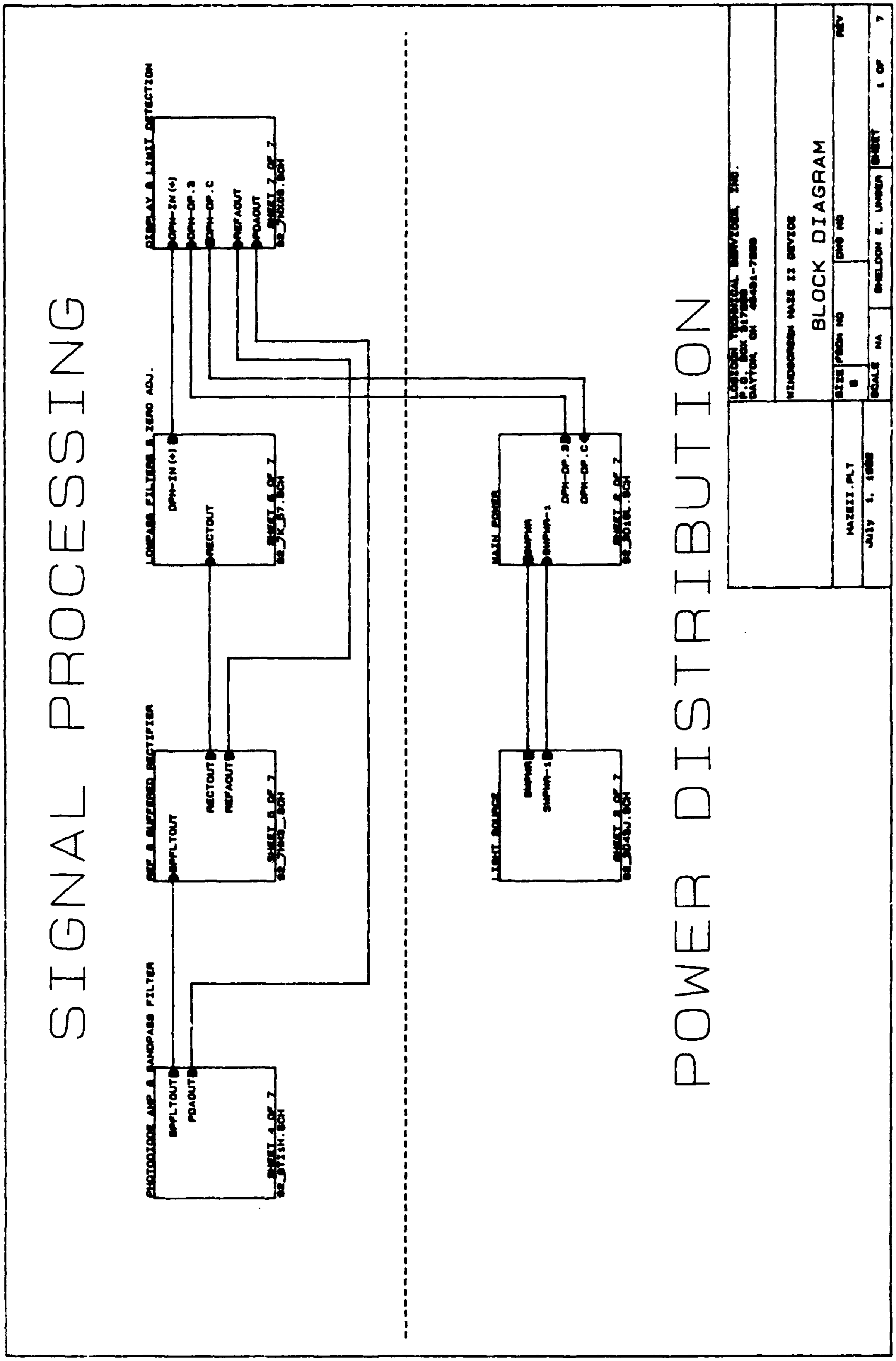
Appendix A, Electronic Design of the Backscatter Haze Device



SIGNAL PROCESSING
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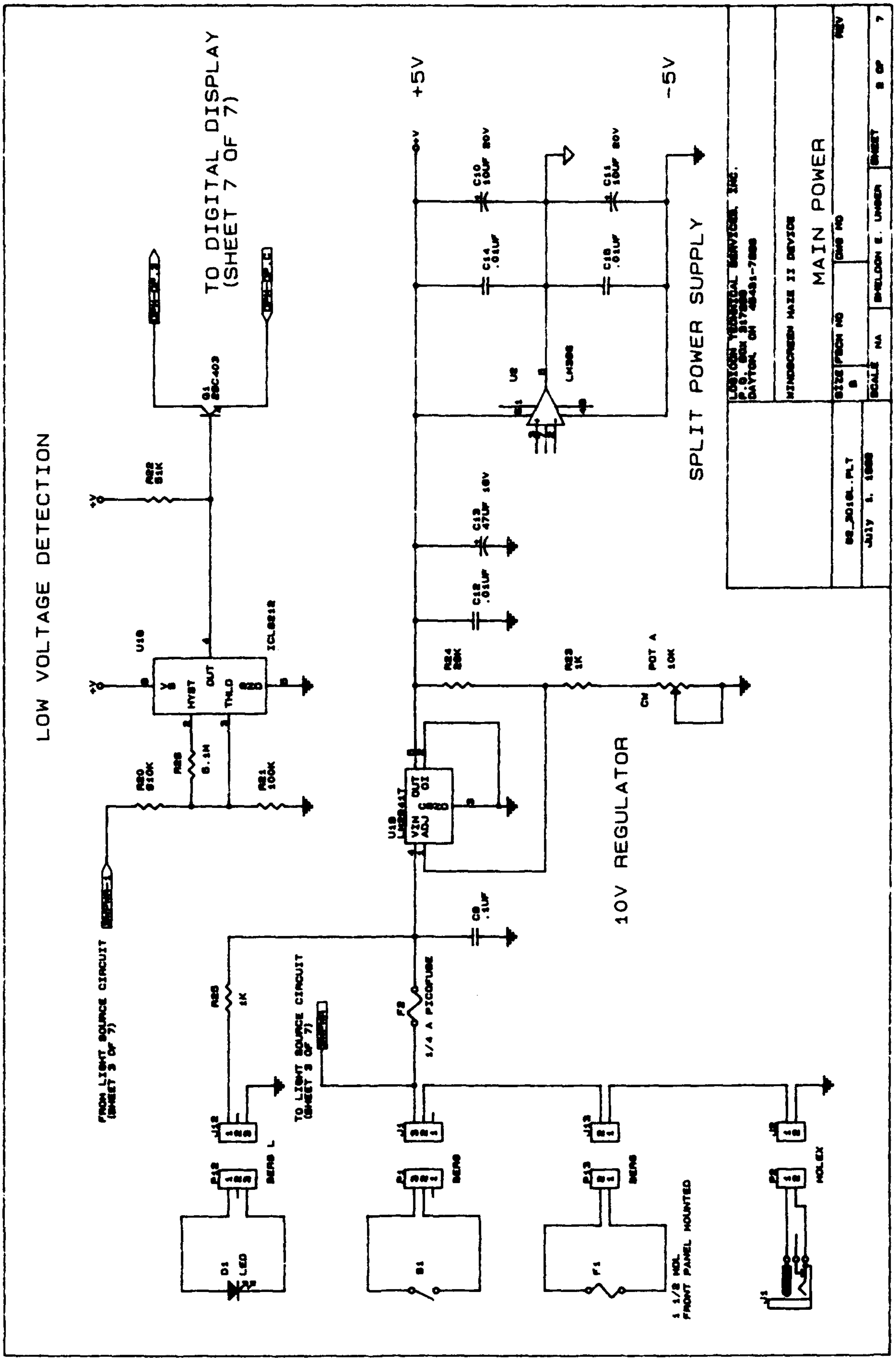
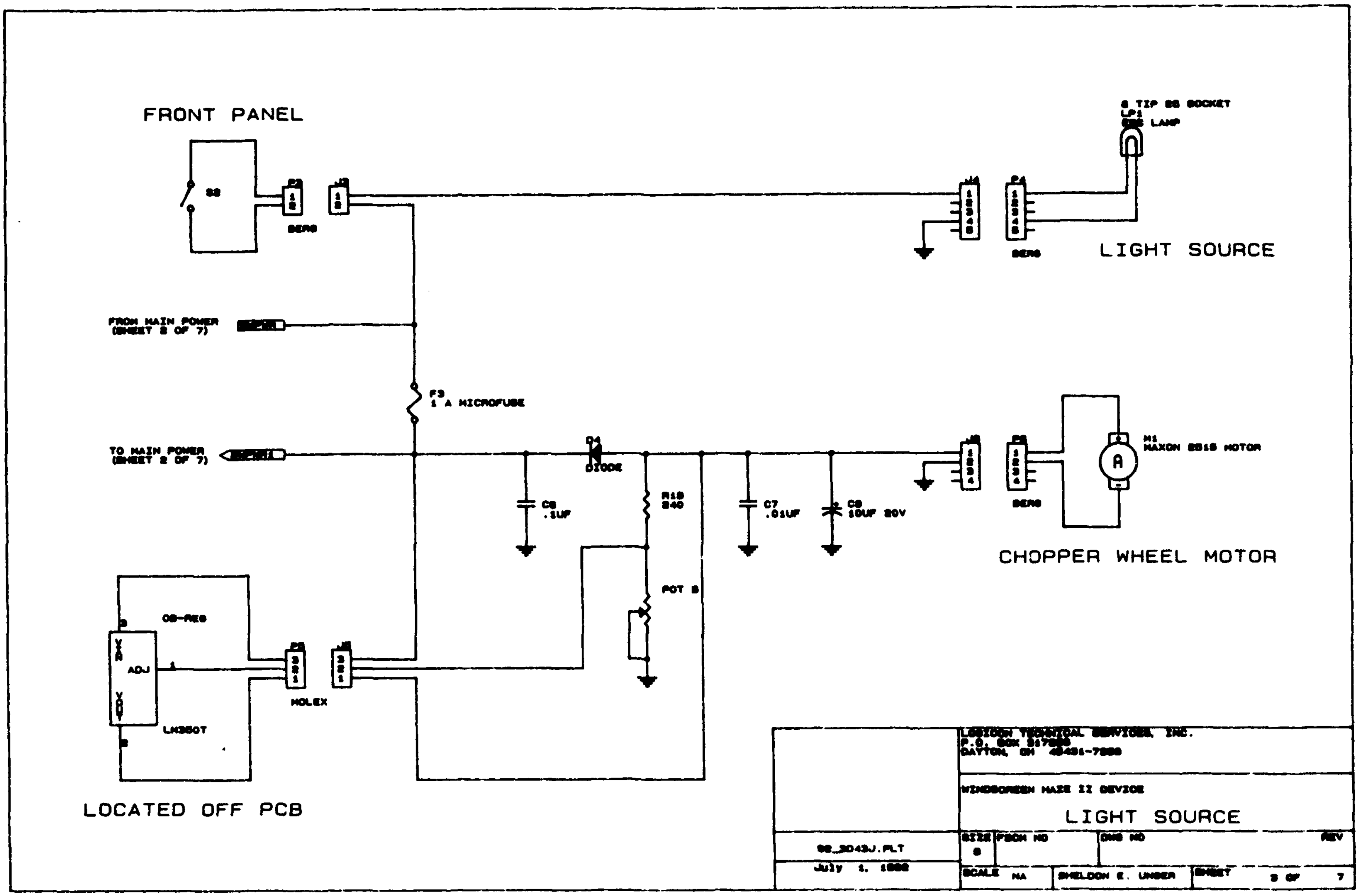
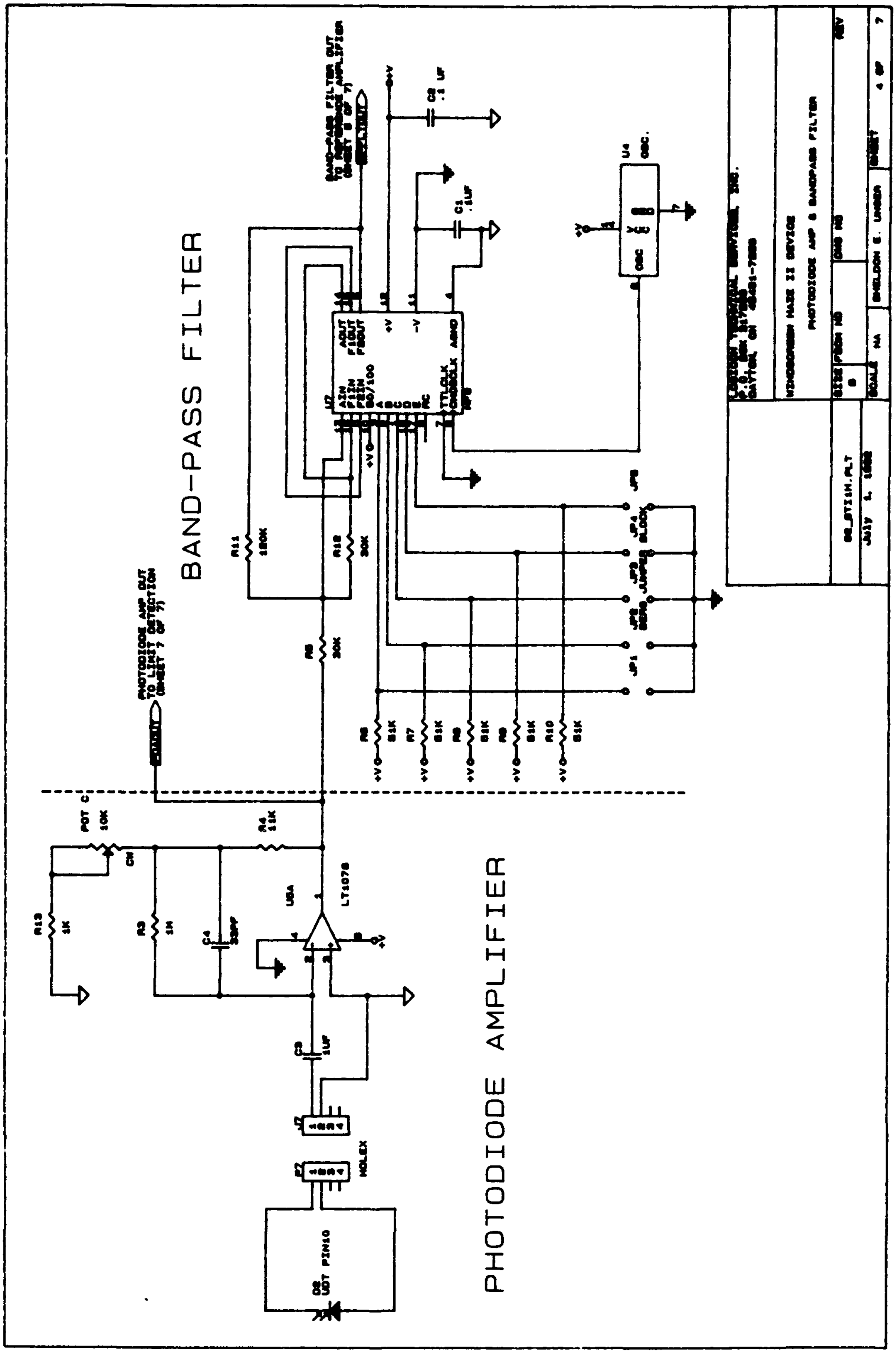
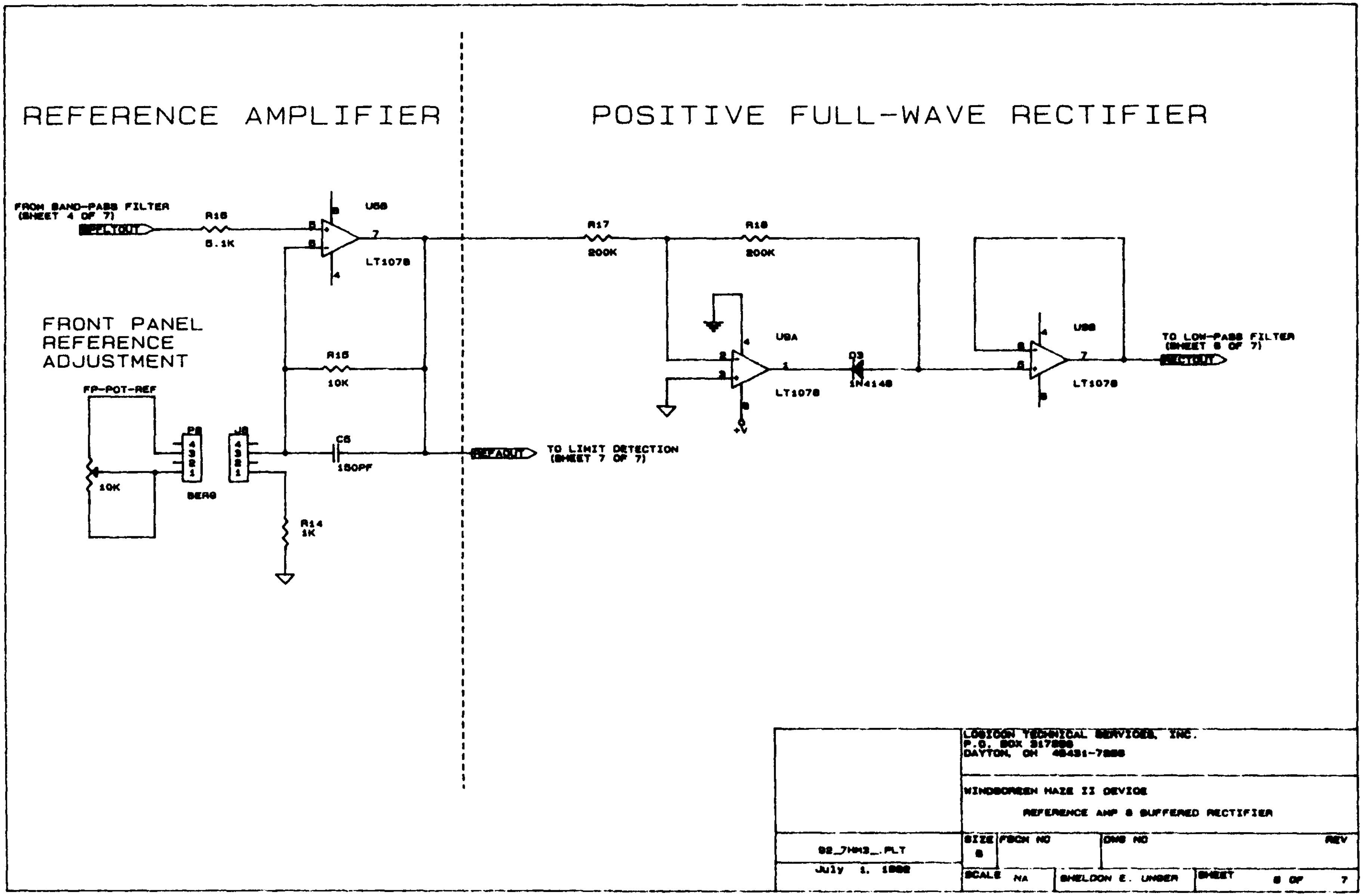
B
SCALE
NA
SHEET
1 OF 7
REV

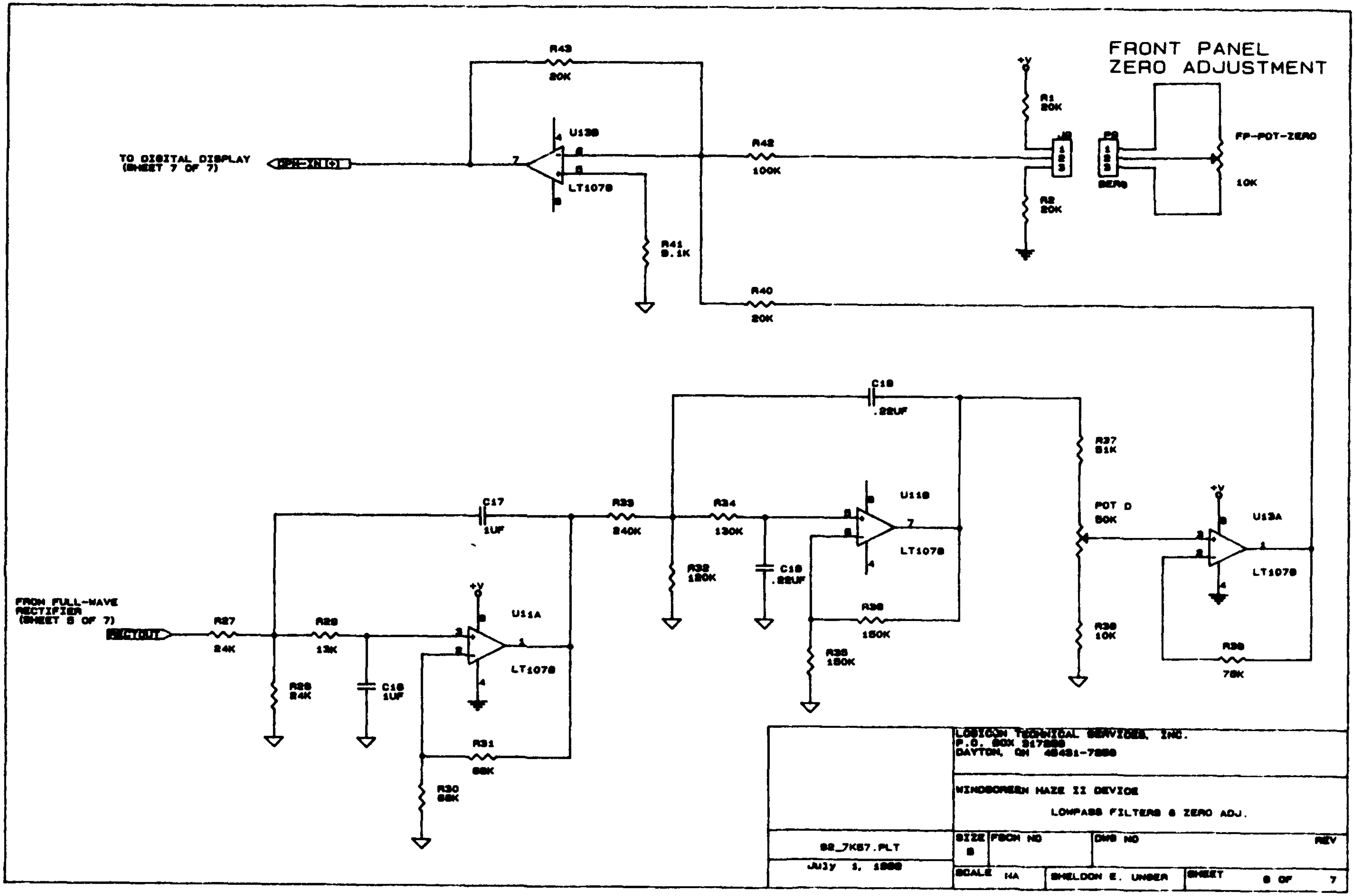


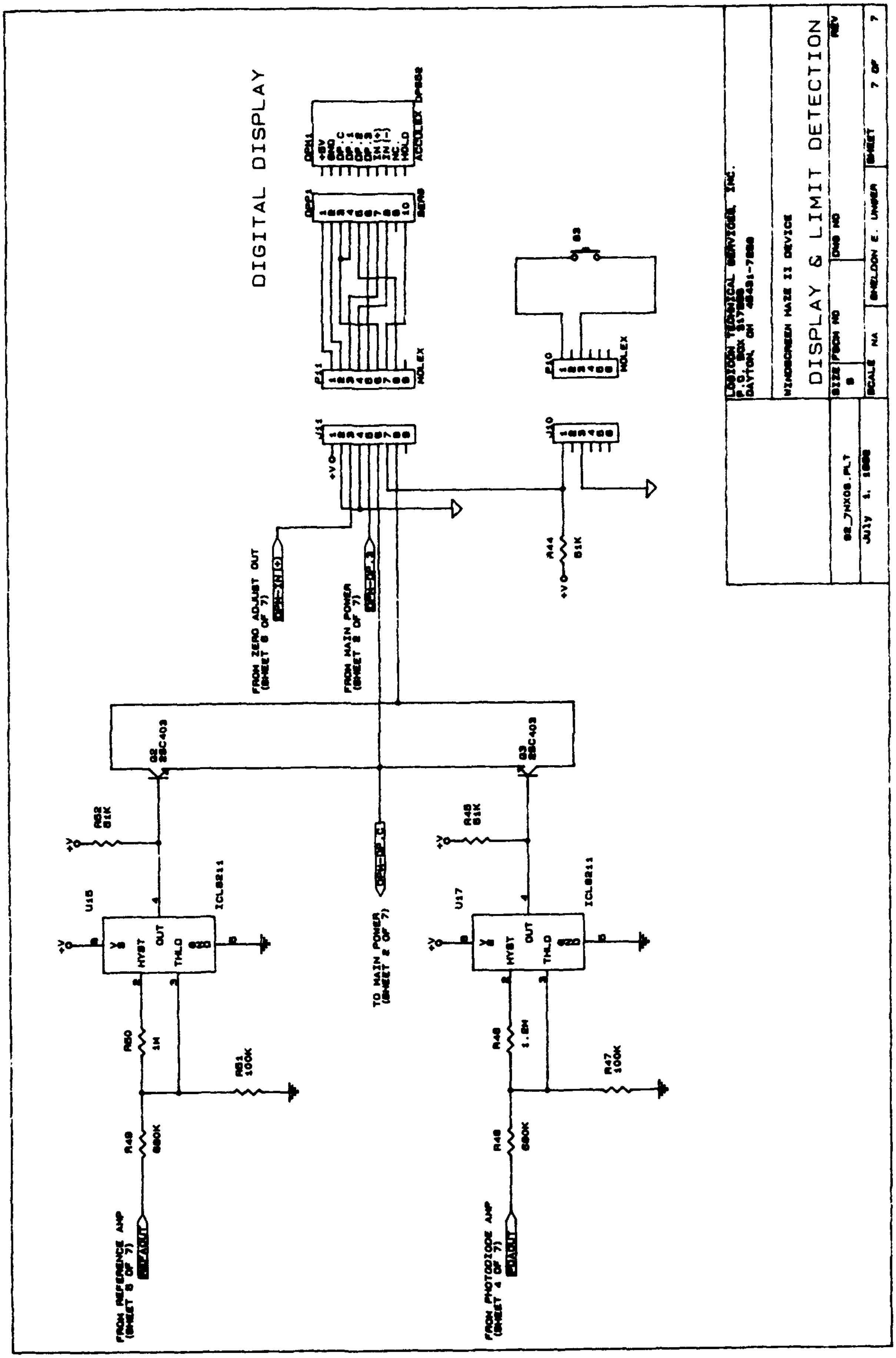
LOW VOLTAGE DETECTION
TO DIGITAL DISPLAY
(SHEET 7 OF 7)
+5V
-5V
SPLIT POWER SUPPLY
10V REGULATOR
MAIN POWER


FRONT PANEL
S2
BERG
LIGHT SOURCE
LAMP
FROM MAIN POWER
(SHEET 2 OF 7)
F3
1 A MICROFUSE
TO MAIN POWER
(SHEET 2 OF 7)
D4
DIODE
C6
.1UF
C7
.01UF
POT
MAXON
MOTOR
CHOPPER WHEEL MOTOR
ADJ
LM350T
MOLEX
LOCATED OFF PCB
DAYTON, OH
WINDSCREEN HAZE II DEVICE
LIGHT SOURCE
SIZE
DWG NO
REV
SCALE
NA
SHELDON E. UNGER
SHEET
OF
7


BAND-PASS FILTER
PHOTODIODE AMPLIFIER


REFERENCE AMPLIFIER
POSITIVE FULL-WAVE RECTIFIER
FROM BAND-PASS FILTER (SHEET 4 OF 7)
R16
5.1K
U5B
LT1078
FRONT PANEL REFERENCE ADJUSTMENT
FP-POT-REF
10K
P8
BERG
J8
R15
10K
C5
150PF
R14
1K
TO LIMIT DETECTION (SHEET 7 OF 7)
R17
200K
R18
200K
U8A
LT1078
D3
1N4148
+V
U8B
LT1078
TO LOW-PASS FILTER (SHEET 6 OF 7)
DAYTON, OH
WINDSCREEN HAZE II DEVICE
REFERENCE AMP & BUFFERED RECTIFIER
SIZE
FSCM NO
DWG NO
REV
SCALE
NA
SHELDON E. UNGER
SHEET


FRONT PANEL
ZERO ADJUSTMENT
FP-POT-ZERO
10K
R1
20K
R2
20K
+V
R42
100K
R40
20K
R43
20K
U13B
LT1078
R41
9.1K
TO DIGITAL DISPLAY
(SHEET 7 OF 7)
FROM FULL-WAVE
RECTIFIER
(SHEET 5 OF 7)
R27
24K
R28
13K
R29
24K
C16
1UF
U11A
LT1078
R31
68K
R30
68K
C17
1UF
R33
240K
R34
130K
R32
120K
C18
.22UF
C19
.22UF
U11B
LT1078
R36
150K
R35
150K
R37
51K
POT D
50K
R38
10K
U13A
LT1078
R39
75K
WINDSCREEN HAZE II DEVICE
LOWPASS FILTERS & ZERO ADJ.
SIZE
B
FSCM NO
DWG NO
REV
SCALE
NA
SHELDON E. UNGER
SHEET
OF
7


DIGITAL DISPLAY
DISPLAY & LIMIT DETECTION
WINDSCREEN HAZE II DEVICE
ICL8211
U15
U17
HYST
OUT
THLD
R50
1M
R51
100K
R49
R47
100K
R44
51K
MOLEX
FROM ZERO ADJUST OUT
FROM MAIN POWER
TO MAIN POWER
FROM REFERENCE AMP
FROM PHOTODIODE AMP
2SC403
Q2
Q3
J11
J10
P11
P10
DPM1
+5V
HOLD
IN(+)
IN(-)
SIZE
SCALE
SHEET
REV

152151