NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

INTERNAL REPORT

MEASUREMENTS OF ATMOSPHERIC ATTENUATION AT 1 MILLIMETER AND A DESCRIPTION OF A PORTABLE SPECTRAL HYGROMETER

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SECTION I — ATMOSPHERIC ATTENUATION MEASUREMENTS

1. Introduction

This report presents the experimental results of an investigation of atmospheric attenuation in the 240-300 Gc (1-mm) radio window measured at Green Bank, W. Va., elevation 2600 feet. Previous workers indicated that the attenuation might vary by as much as 5-6 db with varying atmospheric conditions. Therefore, in order to investigate this problem and to provide accurate extinction data for reduction of astronomical measurements, a series of solar extinction curves were obtained in conjunction with the regular observing program. Section 1 of this report gives a brief description of the instrumentation, observational procedures, and the final results; section 2 gives a brief description of a spectral hygrometer developed in conjunction with the above program. This hygrometer has proven useful in surveys of possible sites for a large mm-wave telescope (NRAO Electronics Division Internal Report No. 31).

2. Instrumentation

The thermal detection radiometer (Low 1965) constructed at NRAO was used to collect the data. This system consisted of a 60-inch paraboloic reflector antenna, a 10 cps chopper, a waveguide feed horn, 1-mm bandpass filters, a germanium bolometer detector (Low 1965), a low frequency parametric amplifier (Biard 1962), a 10 cps amplifier-filter, a synchronous detector, and recorder. Figure 1 is a simplified diagram of the radiometer. When the antenna is directed at the sun the radiation is alternately passed and then blocked by the chopper wheel. This produces a square wave signal at the bolometer terminals which has an amplitude proportional to the brightness temperature difference between the sun and the back of the chopper wheel. When the antenna is pointed at nearby sky the signal is proportional to the

difference between sky and chopper. The back of the chopper wheel is blackened to match the mean sky brightness. This square wave signal is amplified, filtered, and synchronously detected as shown in Figure 1. The output deflections are then recorded as a function of zenith angle and processed to obtain the atmospheric attenuation.

Since the bolometer is a linear power detector over a very wide dynamic range and the synchronous detector is a linear voltage detector, the output deflection is linearly related to the power received at the antenna.

3. Experimental Procedure

A standard observing procedure was developed and utilized throughout the program. This consisted of tracking a point in the sky near the sun and at predetermined intervals, alternately moving the antenna on and off the sun. This on-off procedure was repeated 5 times and constituted a set of measurements. Sets were taken at appropriate intervals throughout a half-day period and from this a solar extinction curve was generated. In addition, a known black body calibration source was introduced in front of the radiometer from time to time to provide a check of receiver gain stability. Finally, readings of elevation angle, temperature, barometric pressure, relative humidity, and total precipitable water were recorded, the latter being taken with the NRAO spectral hygrometer (see Section II for description).

4. Results

Figure 2 illustrates a typical half-day record. Each point represents the average of the five values in one set and is plotted against the appropriate air mass value. A best fit straight line is then drawn through the resulting points. The justification for equating air mass and secant zenith angle is that over the range of zenith angles we were able to observe (0 to 72 max.) the greatest error which could occur was on the order of 2 percent on the higher angles, and was therefore of small consequence.

After extrapolation of the resulting straight line back to zero air mass, the following procedure was used to calculate the total atmospheric attenuation:

1. Determine the receiver output at the 0, 1, 2, and 3 air mass ordinates.
2. Utilizing the formula

$$\Gamma = 10 \log \frac{V_{sun_1}}{V_{sun_2}}$$

where

Γ = attenuation in db/air mass,

V_{sun_1} = receiver output voltage at position 1,

V_{sun_2} = receiver output voltage at position 2,

the attenuation was then calculated using adjacent ordinate pairs (0-1, 1-2, 2-3).

As previously noted, a spectral hygrometer reading was also taken immediately after each set of radiometer determinations, and these were simply averaged over the half-day interval to arrive at a final figure.

A tabulation of the final results is given in Table 1. About 50 percent of the original data was not listed in this compilation for the following reasons:

(1) Any significant cloud cover may or may not produce added attenuation at 1 millimeter. This effect depends to a large extent on the type of cloud and its internal structure and at the present time has not been evaluated thoroughly.

(2) Some days, even though perfectly clear from a meteorological standpoint, displayed a marked deviation from a single best fit straight line at some point during the half-day interval. This generally happened in association with the passage of a frontal system. This phenomenon was also easily observed with the spectral hygrometer.

(3) Local ground fog was at times particularly severe at NRAO, persisting in some cases until well past local noon. The swiftly changing nature of this condition rendered these days data suspect.

In spite of the above, a large number of days yielded excellent data, with a very close grouping of the points about the best fit line.

Finally, Figure 3 shows a plot of attenuation in db per air mass versus precipitable water vapor in millimeters per air mass. The water vapor data were those obtained with the NRAO spectral hygrometer at the time of the attenuation measurements. This graph has proved very useful in predicting observing conditions without going to the trouble and time of setting up the 1 millimeter radiometer.

5. Conclusions

The data which are presented give the variation in attenuation over the entire 1-mm window for the driest conditions at Green Bank. The effects of clouds and ground fog have been purposely avoided. A good general survey of the distribution of water vapor as a function of elevation, season and geographic location within the U.S. is contained in Weather Bureau Technical Paper No. 10, "Mean Precipitable Water in the United States." The present results clearly show the necessity of making 1-mm observations from a dry site.

TABLE 1

COMPILATION OF ATTENUATION DATA

Date	Attenuation db/air mass	Water Vapor mm/air mass	Remarks
7/7/64	8.4	13.5	Very light haze
9/15/64	4.3	9.3	Very light haze
9/16/64	3.7	10.2	Clear
10/8/64	2.6	6.2	Clear
10/12/64	2.6	6.3	Clear
10/14/64	4.9	10.0	Very light haze
11/2/64	2.1	7.4	Clear
11/6/64	2.5	5.1	Clear
11/13/64	2.2	5.0	Clear
11/17/64	2.4	6.3	Clear
11/23/64	1.1	3.0	Clear
12/1/64	1.5	3.1	Clear
12/9/64	1.3	2.4	Clear
12/13/64	2.6	5.8	Clear
12/14/64	0.7	2.7	Clear
12/15/64	0.6	1.5	Clear
12/18/64	0.4	1.4	Clear
12/29/64	2.0	6.5	Clear
12/31/64	1.4	3.2	Clear
1/11/65	1.5	3.2	Clear
1/14/65	1.1	1.9	Clear
1/15/65	1.5	4.9	20 percent cloud cover
1/17/65	1.8	4.5	Clear
1/19/65	2.1	5.1	Clear
1/23/65	1.6	4.6	Clear
1/25/65	1.8	4.7	Clear
2/3/65	1.1	1.8	Very light haze
2/4/65	0.8	1.9	Clear
2/5/65	0.35	1.4	Clear
2/15/65	1.2	3.2	Clear
2/24/65	2.4	5.6	Clear
2/27/65	1.8	6.1	Clear
3/1/65	2.7	6.7	Clear
3/14/65	2.9	7.6	Clear
3/30/65	2.4	6.1	Clear
3/31/65	3.8	8.4	Clear
4/28/65	4.0	9.3	Clear
5/4/65	6.1	11.4	Clear

SECTION II — THE SPECTRAL HYGROMETER

1. General

Early in the 1 millimeter observing program, a need developed for a simple hygrometer for measuring the amount of water vapor in a vertical column of the atmosphere. This instrument would serve the dual purpose of allowing quantitative estimates of the observing conditions to be made prior to setting up the 1 millimeter radiometer, and also would provide a means of conducing site surveys for future millimeter telescopes. The U. S. Weather Bureau had developed a recording spectral hygrometer (Foster, Volz, Foskett, 1963) based on a technique first described by Fowle (Ap. J. 1912). Our portable instrument is based on these previous workers' results with some modifications and further refinements. This task was undertaken, and by late 1963 essentially complete. The following sections give the more pertinent details along with an evaluation of the results obtained.

2. Instrument Description

a. Theory — Figure 1 shows an outline drawing of the spectral hygrometer. Basically, the instrument compares the relative intensity of direct solar energy transmitted in a water-vapor absorption band against that of a nearby spectral region having essentially no absorption. For reasons stated in Volz's manuscript, the region of absorption is centered at 0.935 microns and the reference region at 0.880 microns. Narrow band-pass interference filters isolate the two spectral regions, and a photodiode is used as a radiation sensor. The instrument is so designed that the ratio of the photocurrents is proportional to the ratio of the transmitted radiant energies; this ratio is an index of the amount of water vapor in the sensing path using an empirically determined calibration curve. The latter quantity can then be divided by the solar air mass in order to obtain the vertical atmospheric water-vapor content or total precipitable water. Since pressure broadening of the absorption lines making up the 0.935 μ band effects the transmission thru the band, this type of instrument is subject to errors from varying height distributions of water vapor.

b. Optical components — Incident sunlight falling on the entrance slit first passes through a Corning sharp cutoff red filter (type C. S. No. 2-61 - transmittance < 0.5 percent at wavelengths below 0.590 μ) which serves as both protection from the weather as well as to prevent the transmission of radiation through possible passbands of higher order. It next passes through one of the two first order, narrow-band-pass interference filters, whose characteristics are shown in the spectrophotometric curves of Figures 2 and 3. Note that the 880 mμ filter shows a transmittance of about 62 percent in the desired region, and only 4.6 and 4.3 percent in the unwanted regions of 1.1 μ and 2.0 to 2.3 μ. However, the 935, in addition to its peak at 935 μm, has peaks of 0.3 percent at 720 μm, 1 percent at 770 μm, 70 percent at 1.8 μ, 78 percent at 1.35 μ, 78 percent at 1.62 μ, and 73 percent at 1.97 μ, together with broad transmittance between 1.1 and 2.6 μ.

c. Photodiode — This unwanted radiation falling outside the pass-band is essentially eliminated, however, by the response curve of the photodiode which is shown in Figure 4. This device is a Texas Instruments Type LS-400, NPN silicon planar photodiode (TI Appl. Note 1962) which exhibits excellent sensitivity, temperature stability, and linear response. A careful calculation of the responses outside the pass-band yields an error of about 2 percent due to unwanted radiation for both filters, which was small enough to be neglected.

The remainder of the circuit is quite straightforward; the 9 V battery supplies bias for the photodiode, R_1 and R_2 are scaling resistors, and the meter is a highly sensitive 0-10 μA taut-band type. An on-off switch is not needed since the dark current is less than 10^{-7} amp.

d. Calibration — The calibration curve for hygrometer A3-1 is shown in Figure 5. The ratio as determined by the instrument is plotted along the Y axis; precipitable water vapor (x in cm) is shown along the X axis. This curve was established in the following manner: Fowle's data from absorption tube experiments were used to established the shape of the curve at low water vapor levels. Comparison with Volz's instrument at the U. S. Weather Bureau in Washington at higher water vapor levels provided an absolute reference since his instrument had been empirically calibrated against radiosonde data. In addition, A3-1 was flown in a U-2

aircraft at Lockheed Aircraft Company. After correcting on the ground for the effect of the airplane canopy, the reading at high altitude provided the zero point. Finally, duplicate instruments constructed at NRAO were then calibrated against A3-1. A check of the long-term stability of A3-1 was made after a 1 1/2 year period of almost constant use by flying again in a U-2 aircraft (courtesy of Davis-Monthan Air Force Base, Tucson, Arizona).

3. Evaluation

The instrument's operation, both in the laboratory and in the field, has demonstrated its dependability and relative accuracy. Changes in total precipitable water as detected by the spectral hygrometer were quite consistently comparable to those changes indicated by the 1 millimeter radiometer. Further tests have shown that the accuracy is not degraded by ambient temperature variations or by intensity fluctuation of the incident radiation. This feature is quite important for a portable instrument and is possible only because of the linearity of the photodiode.

Unfortunately, we have not found a simpler method of calibration or a method of transferring the calibration of A3-1 to other instruments except by the time consuming process of inter comparison. This has restricted the widespread use of the instrument.

4. Acknowledgements

The authors wish to express their appreciation to Messrs. Frank Bash, Wade Poteet and Ellis Remsberg for their assistance in the construction and testing of the hygrometer.

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Fowle, F. E., Ap. J., Vol. 35, p. 149, 1912.

Texas Instruments Application Note, "Silicon Planar Photo Device", LS-400, Dec. 1962.

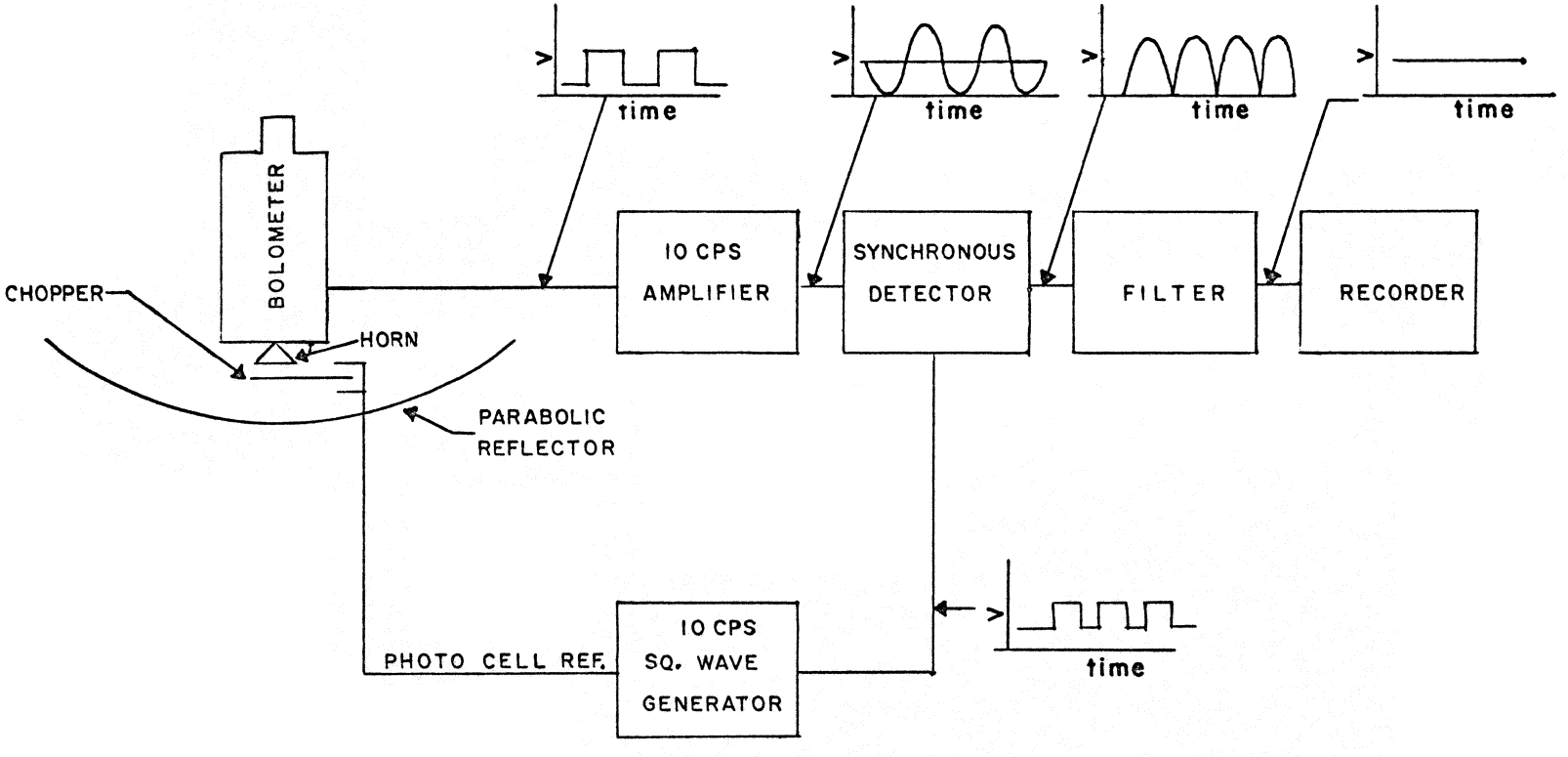
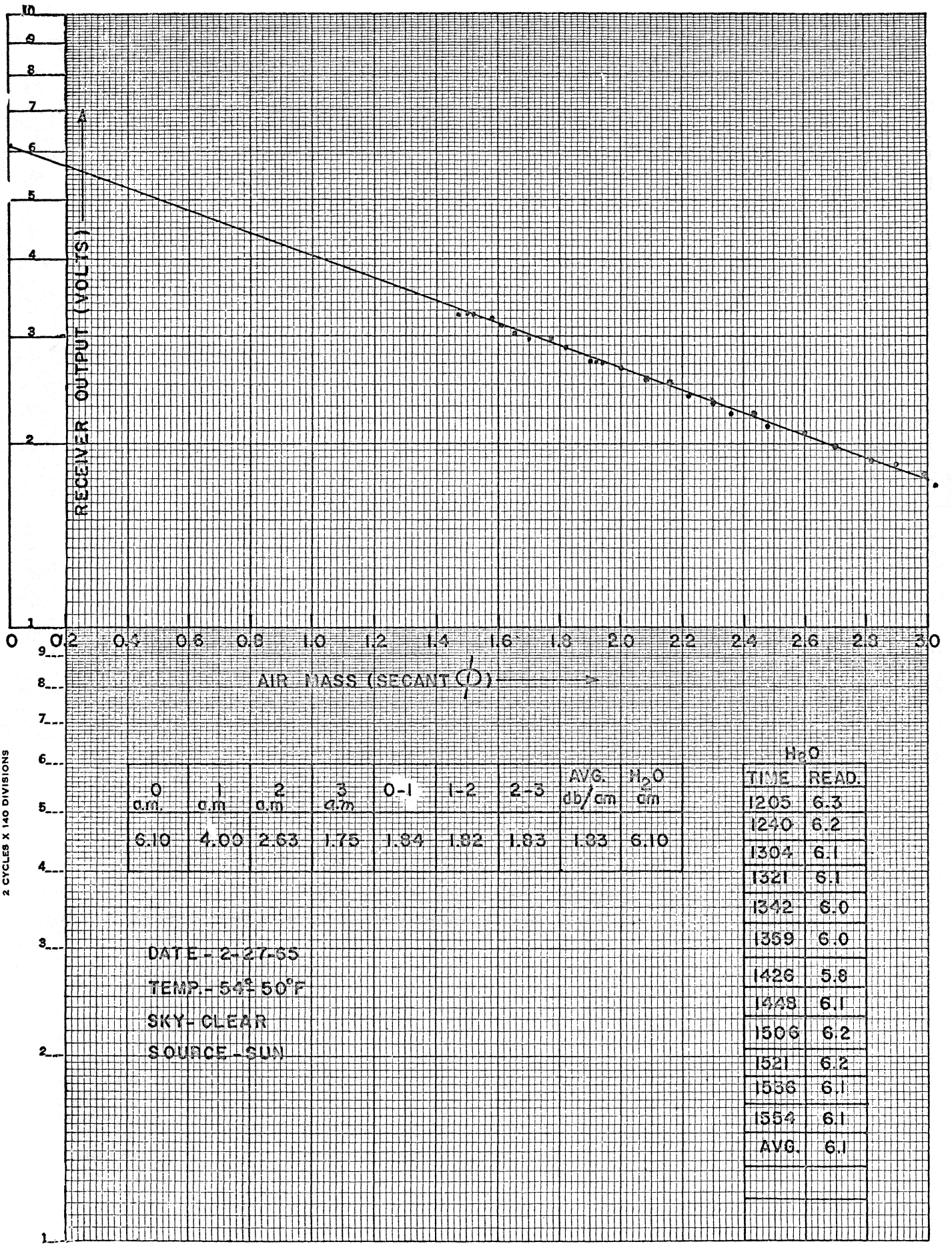


FIG. 1 BLOCK DIAGRAM 1-MM RADIOMETER



0 a.m.	1 a.m	2 a.m	3 a.m	0-1	1-2	2-3	AVG. db/cm	H_2O cm
6.10	4.00	2.63	1.75	1.84	1.82	1.83	1.83	6.10

DATE - 2-27-65
TEMP. - 54°-50°F
SKY - CLEAR
SOURCE - SUN

H_2O TIME	READ.
1205	6.3
1240	6.2
1304	6.1
1321	6.1
1342	6.0
1359	6.0
1426	5.8
1448	6.1
1506	6.2
1521	6.2
1536	6.1
1554	6.1
AVG.	6.1

KEUFFEL & ESSER CO. MADE IN U.S.A.
2 CYCLES X 140 DIVISIONS

FIG. 2 - SOLAR ATTENUATION

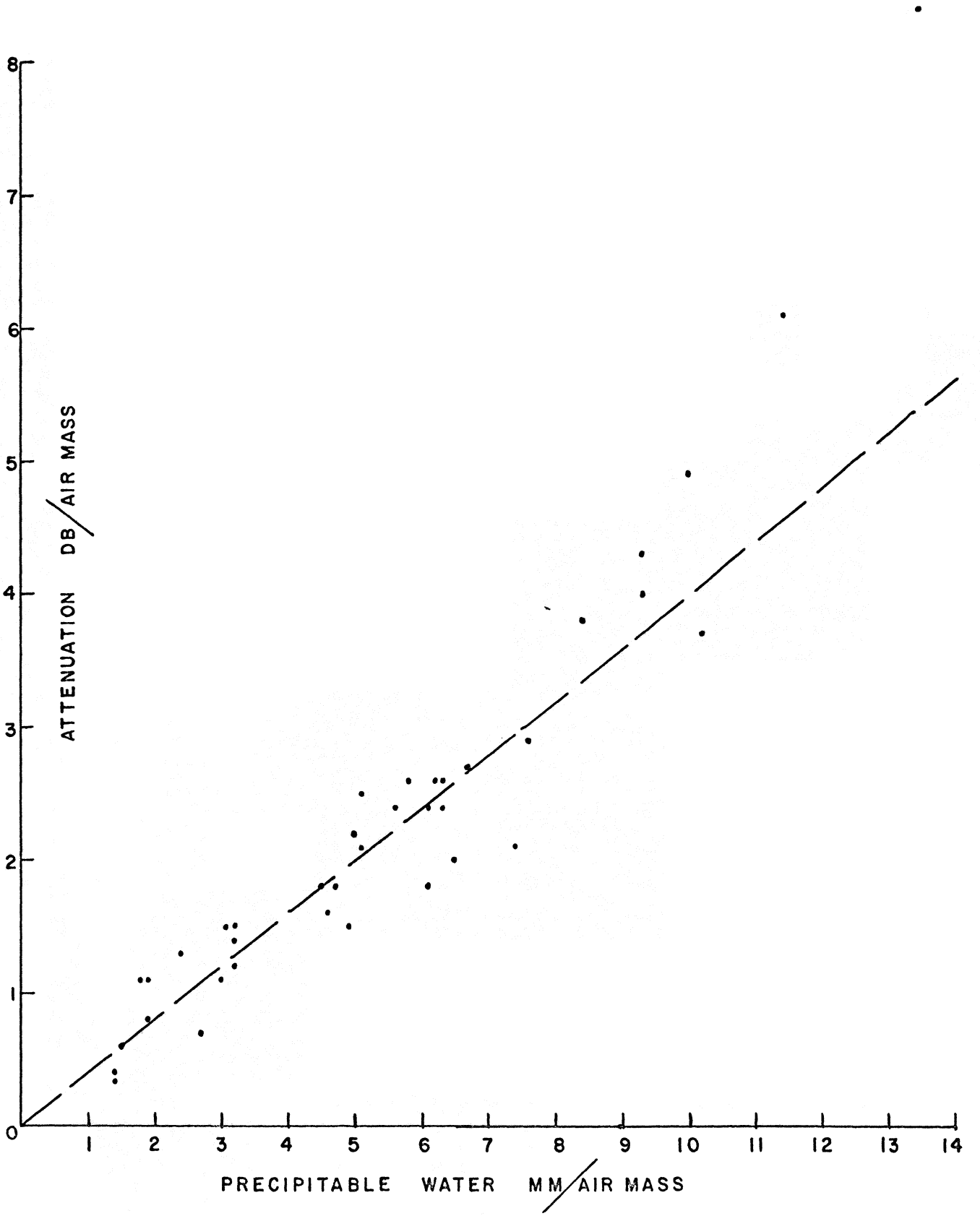


FIG. 3 ATMOSPHERIC ATTENUATION AT 1-MM

R1-100K
R2-5K
Note-R2 must be chosen for each diode filter combination to keep all deflections on scale.

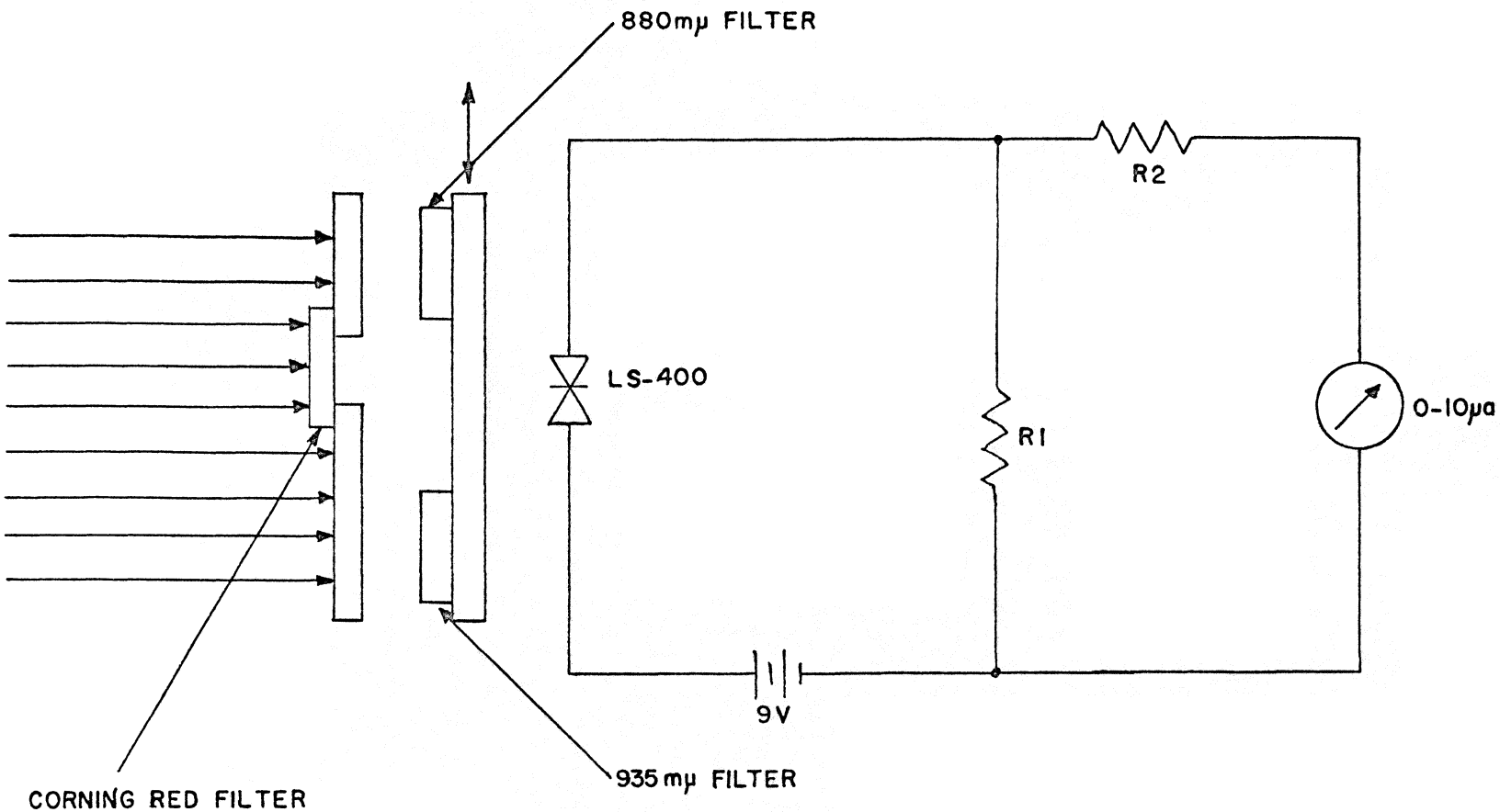


FIG.1 OUTLINE DRAWING OF SPECTRAL HYGROMETER

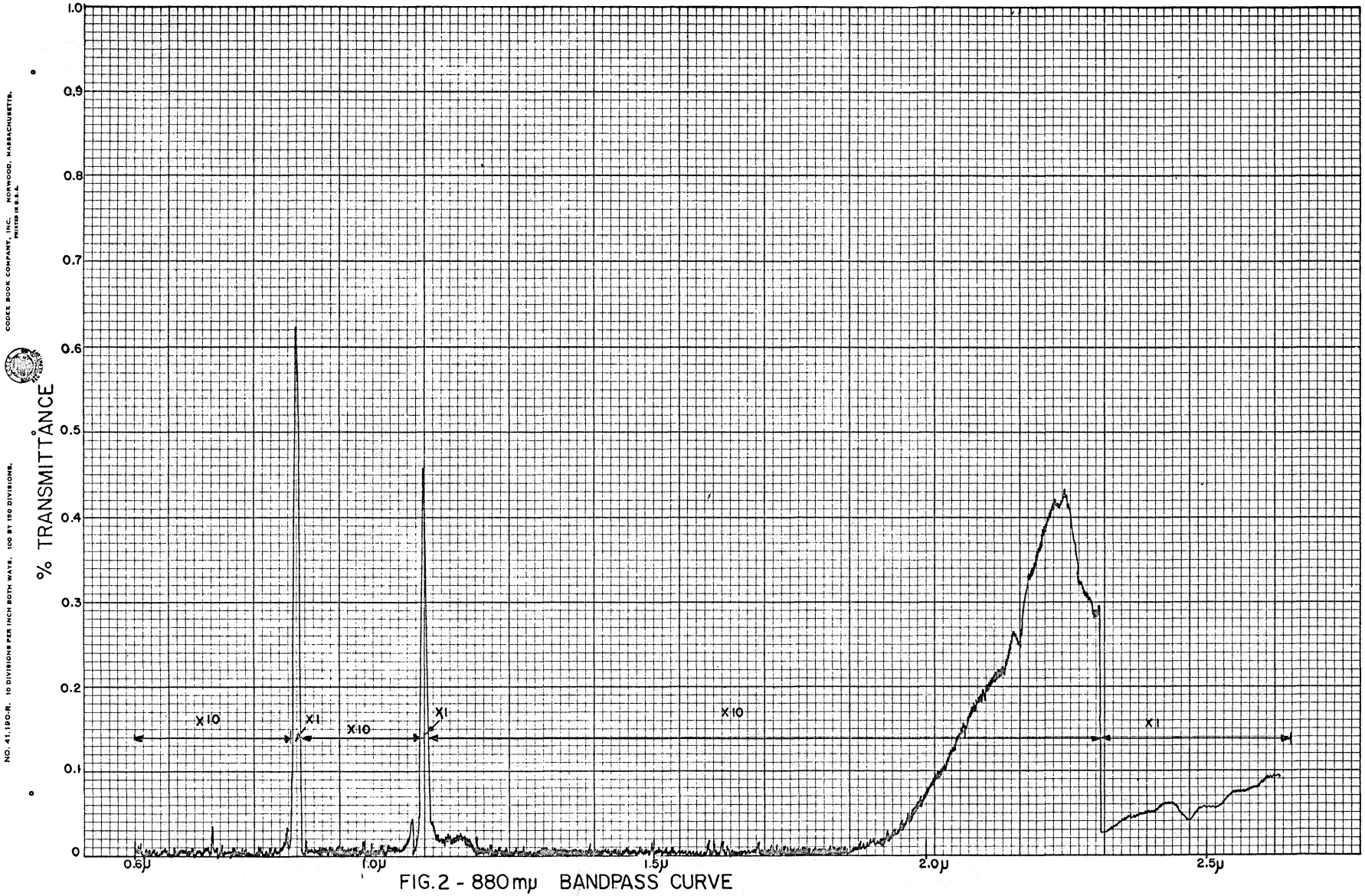


FIG. 2 - 880 mμ BANDPASS CURVE

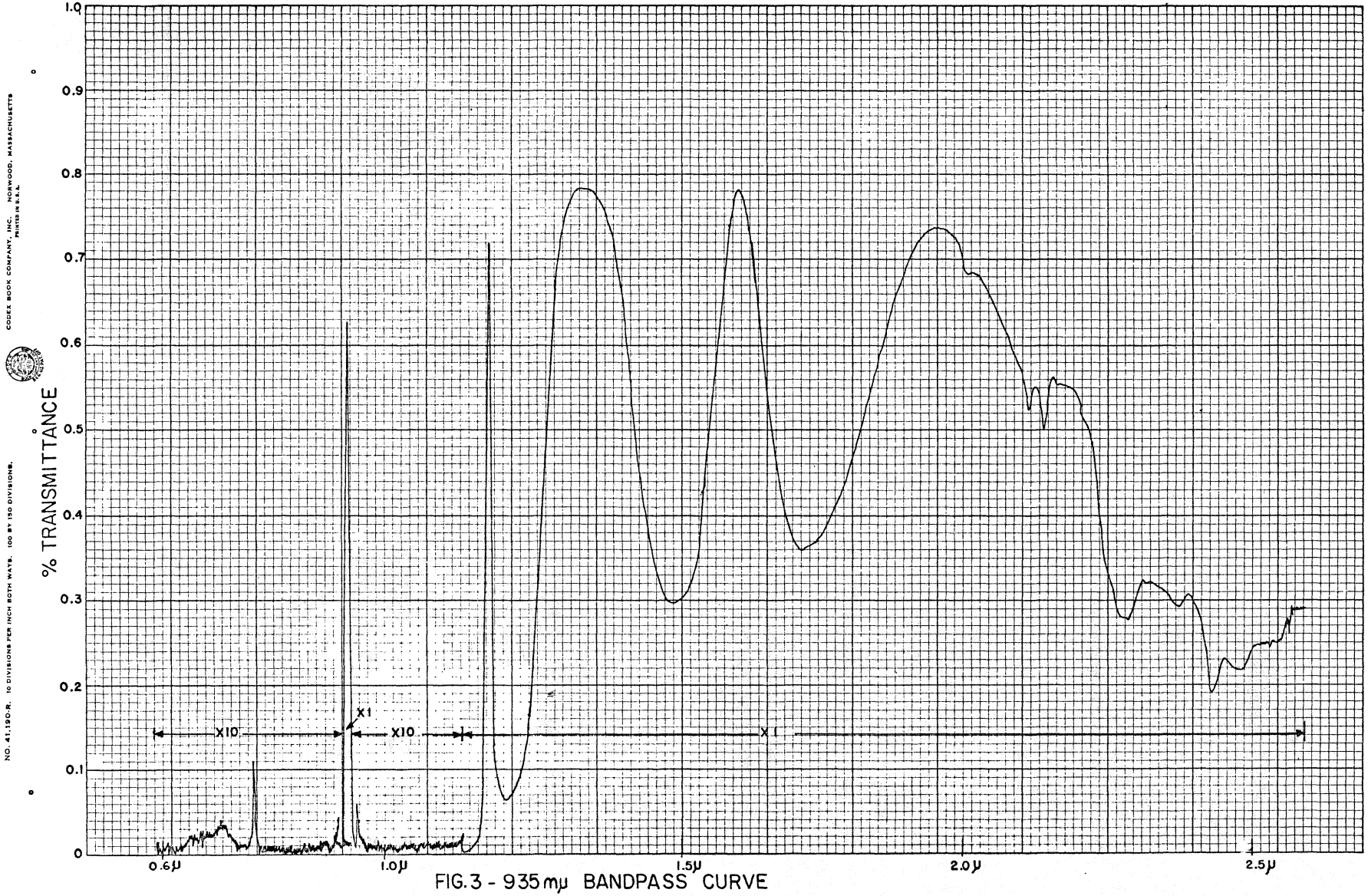


FIG. 3 - 935 mμ BANDPASS CURVE

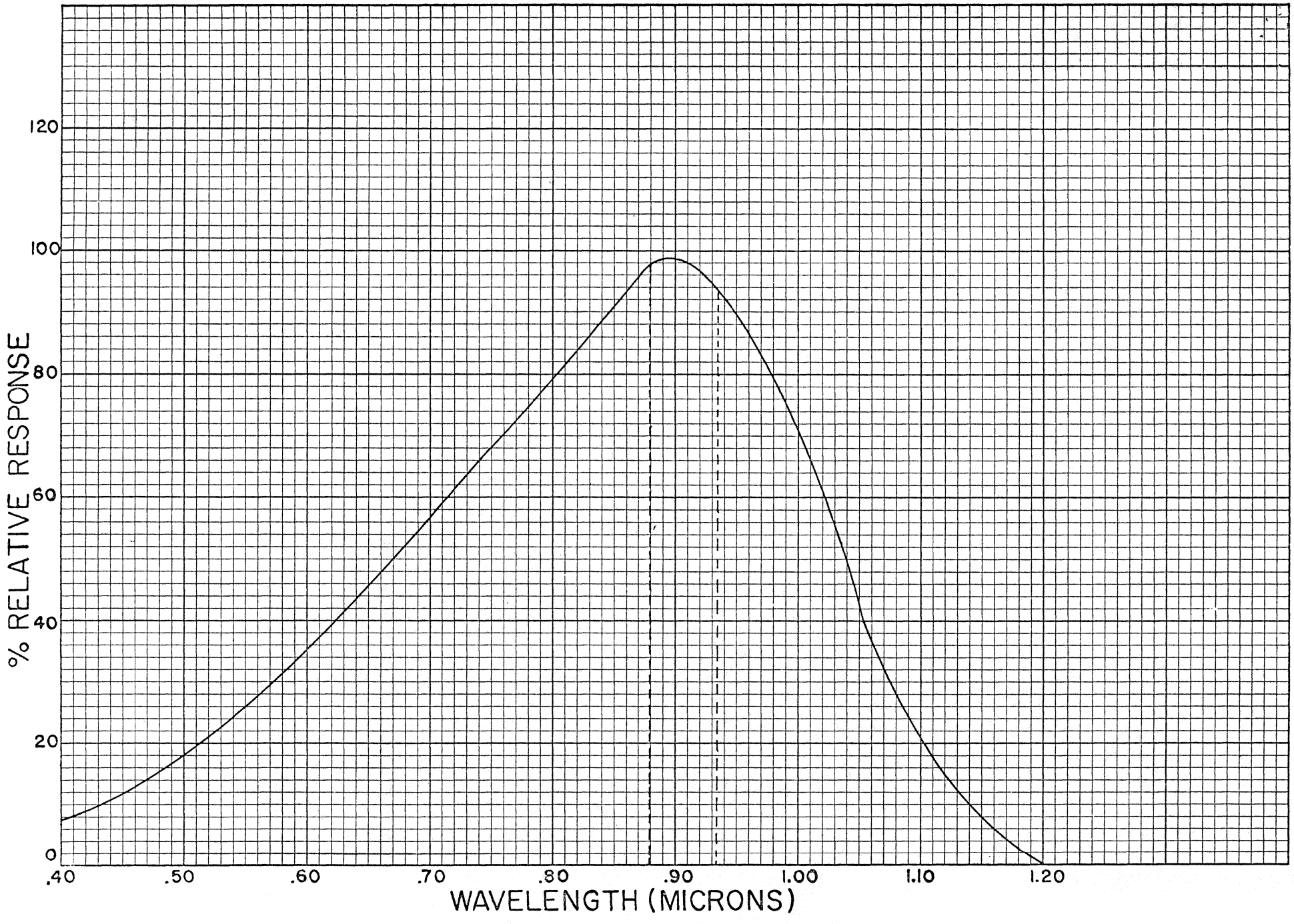


FIG. 4 LS-400 SPECTRAL RESPONSE CURVE

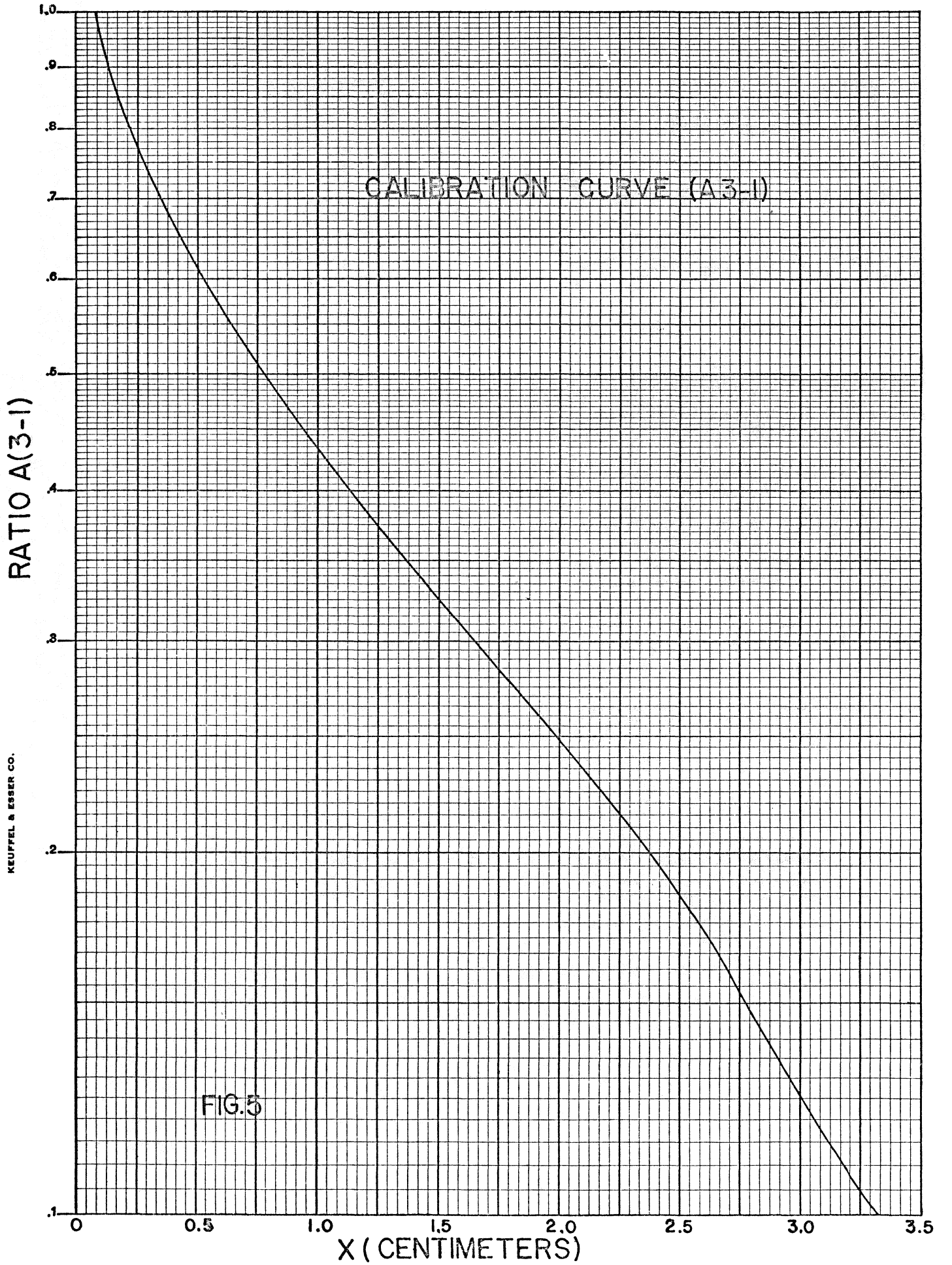

CALIBRATION CURVE (A3-1)
RATIO A(3-1)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
X (CENTIMETERS)
KEUFFEL & ESSER CO.

FIG.5