MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Research Laboratory of Electronics
Cambridge 39, Massachusetts

April 28, 1960

PROPOSED PROGRAM

TO DETECT THE GALACTIC DEUTERIUM LINE

For an Eighteen-Month Period, June 1, 1960 through November 30, 1961

Abstract---A procedure is outlined for detecting the 327 mc. deuterium line for the purpose of determining the galactic deuterium-to-hydrogen ratio. The proposed detection system makes use of digital autocorrelation and Fourier transformation to obtain the spectral density by use of the Wiener theorem. Radio astronomy and electronic data processing aspects of the problem are discussed.

Principal Investigator
S. Weinreb, Graduate Student in the
Department of Electrical Engineering

J. B. Wiesner, Director
Research Laboratory of Electronics

Carl F. Floe, Vice President for
Research Administration

TABLE OF CONTENTS

APPLICATION OF STATISTICAL COMMUNICATION THEORY TECHNIQUES TO THE DETECTION OF THE GALACTIC DEUTERIUM LINE

1.0 Introduction

The Russian scientist, Shklovsky, in 1952 predicted that it may be possible to detect emission or absorption of UHF radiation by deuterium in our galaxy [1]. Deuterium, an isotope of hydrogen, under suitable conditions will emit or absorb radiation in a narrow band of frequencies centered at approximately 327 megacycles. This radiation will be referred to as the deuterium line and is analogous to the hydrogen line at 1420 megacycles, which has been of intense interest in radio astronomy since its detection by Ewen and Purcell in 1951.

It is of importance to cosmological theory that the intensity of the deuterium line be compared to the hydrogen line, for on the basis of this measurement the galactic deuterium-to-hydrogen abundance ratio can be determined. This figure is fundamental to the astrophysicist's study of element synthesis [2]. There is reason to speculate that the deuterium-to-hydrogen abundance ratio may be equal to the figure of one to 6700 which is the value which has been found on earth and in meteorites.

There have been at least four attempts to detect the deuterium line [3,4,5,6]. The earliest of these, a Soviet attempt, claimed (and later retracted) detection of the deuterium line at an intensity which gave a deuterium-to-hydrogen abundance ratio of 1/300. Subsequent attempts in Australia and England with progressively

TABLE I

SUMMARY OF PREVIOUS ATTEMPTS TO DETECT THE 327 MC. DEUTERIUM LINE

	GETMANZEV STANKEVITCH AND TROITSKY (1955)	STANLEY AND PRICE (1956)	ADGIE AND HEY (1957)	ADGIE (1958)
ANTENNA DIAMETER	12'	80'	22'(?)	250'
RECEIVER NOISE T_r	3000°	1800°	900°	
BANDWIDTH Δf	15 KC.	16 KC.	16 KC.	15 KC.
NUMBER OF SCANS AND TIME CONSTANT	? 90 SEC.	8 - 60 SEC. 4 -210 SEC. 5 - 60 SEC.	34 - 300 SEC.	18 HOURS
OBSERVATION PROCEDURE	-	SOURCE DRIFTS THROUGH ANTENNA AS FREQUENCY IS SCANNED 200 KC.	ANTENNA TRACKS SOURCE AS FREQUENCY IS SCANNED 100 KC.	ANTENNA TRACKS SOURCE
TOTAL BACKGROUND TEMPERATURE $T_p + T_c$	300°	800°	160°	EST 7000°
CONCLUSION	$n_d/n_h \approx 1/300$	$n_d/n_h < 1/1000$	$n_d/n_h \ll 1/2000$	$n_d/n_h \ll 1/4000$

more and more sensitive apparatus have not detected the line and have successively established an upper bound to the abundance ratio of 1/1000, 1/2000, and finally in 1958, 1/4000. Some of the details of these experiments are given in Table I. It is noteworthy that the upper bound of 1/4000 is just short of the likely terrestrial value of 1/6700 and was obtained using state of the art receiving apparatus (multichannel radiometer, 250' antenna at Jodrell Bank).

The goal of this project will be to determine with a high degree of certainty if the galactic deuterium-to-hydrogen abundance ratio is the same as the terrestrial value of 1/6700. The sensitivity of the apparatus will be adequate to set an upper bound of 1/15,000 if no line is detected. The required improvement in sensitivity will be obtained by the use of digital processing of the information using statistical communication theory techniques. In later sections of this proposal, the data processing system will be described. Before proceeding to this we will discuss the radio astronomical aspect of the problem and point out the effect on signal-to-noise ratio of the region of observation, antenna size, and receiver noise.

2.1 Radio Astronomical Aspects of the Problem.*

The first realization which must be made is that although the interaction with radiation of an individual deuterium atom is an extremely narrow band (10^{-13} c.p.s.) process, the collective interaction of a large number of these atoms will be dispersed due to Doppler shift. The thermal motion of these atoms causes a line

* A more detailed account of this section is given in (7); excellent background material is presented in (8).

broadening which is of the order of kilocycles. The signal which arises can be described as a narrow-band Gaussian process, as it is the result of an extremely large number of sinusoidal generators (atoms) adding with random phase. It is important to note that this signal has much the same character as thermal noise, a fact which has bearing on the statistical detection problem.

A second Doppler effect will be a shift of line frequency due to relative motion of the earth with respect to the region of the galaxy containing the deuterium gas. Fortunately, hydrogen line observations give us quantitative information about both of these Doppler effects and we can estimate the shape of the line and its center frequency quite accurately. This fact is of great aid to the statistical detection problem.

The collective action of a large number of deuterium atoms in an antenna beam can be described by a quantity known as the opacity, which is a measure of the coupling of the thermal energy of the gas to the radiation field. It is a function of frequency (i.e., it is zero at frequencies other than near the line frequency), properties of the atom, and the number of atoms in the antenna beam. It is shown in (7) that the peak opacity of deuterium, τ_d, is related to that of hydrogen, τ_h , by

$$\tau_d = \tau_h \cdot 4 \frac{N_d}{N_h} \qquad (1)$$

where N_d/N_h is the deuterium-to-hydrogen abundance ratio. Hydrogen is distributed quite widely in the plane of the galaxy and we do not expect the deuterium-to-hydrogen ratio to vary at different positions. The highest observed values of τ_h are of the order of 3, which results in a τ_d of the order of 10^{-4} for $N_d/N_h = 1/6700$.

A description of the received signal in terms of the opacity and various (known) temperatures follows from Figure 1. The figure depicts a general configuration which may be found for an antenna beam directed into the plane of the galaxy. The discrete source (radio star), of temperature, T_p, is a high intensity source which subtends a solid angle which is much smaller than present antenna beams. These discrete sources are usually many beamwidths apart and hence may or may not be found in the antenna beam. However, the gas and the continuous background source will always be found in some degree for an antenna directed in the plane of the galaxy. It can be shown that the equation describing the antenna temperature is the following [9]:

$$T_a = T_p e^{-\tau_p} + T_c e^{-\tau_c} + (1 - e^{-\tau_c}) T_g \qquad (2)$$

where the symbolism is as follows:

T_p is the contribution to antenna temperature of a source much smaller than the antenna beam. It is a function of antenna size, and may run from zero to several thousand degrees.

τ_p is the opacity averaged in the small solid angle, Ω_p, subtended by the above source.

T_c is the brightness temperature of the spatially continuous or slowing varying background. At 327 mc. it should run from about 80° to 400° in the plane of the galaxy.

τ_c is the opacity averaged in the solid angle, Ω_a, of the antenna beam. It includes τ_p.

T_g is the spin temperature of the hydrogen and deuterium gas in the antenna beam. It can be assumed to be 125° K, for both deuterium and hydrogen.

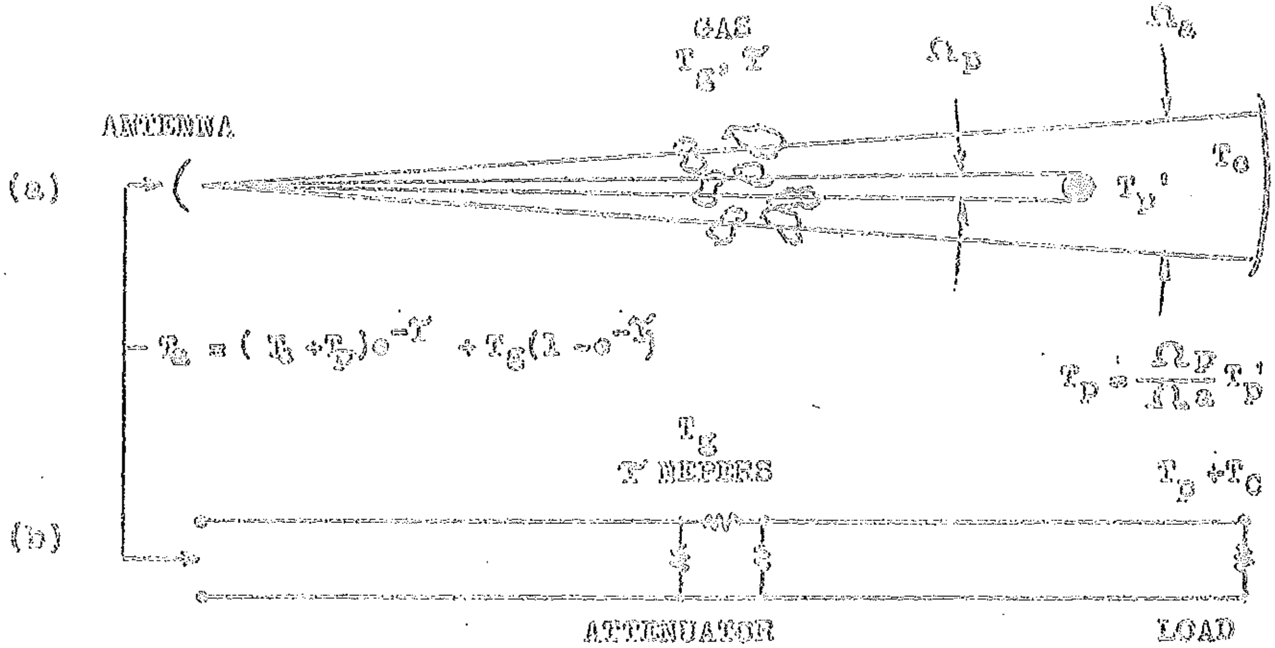


FIGURE 1 - A general configuration which might be found in an antenna beam directed into the galactic plane. T_p' represents a point source and T_c the spatially continuous background radiation. (b) This is the transmission line analogy to the situation shown in (a).

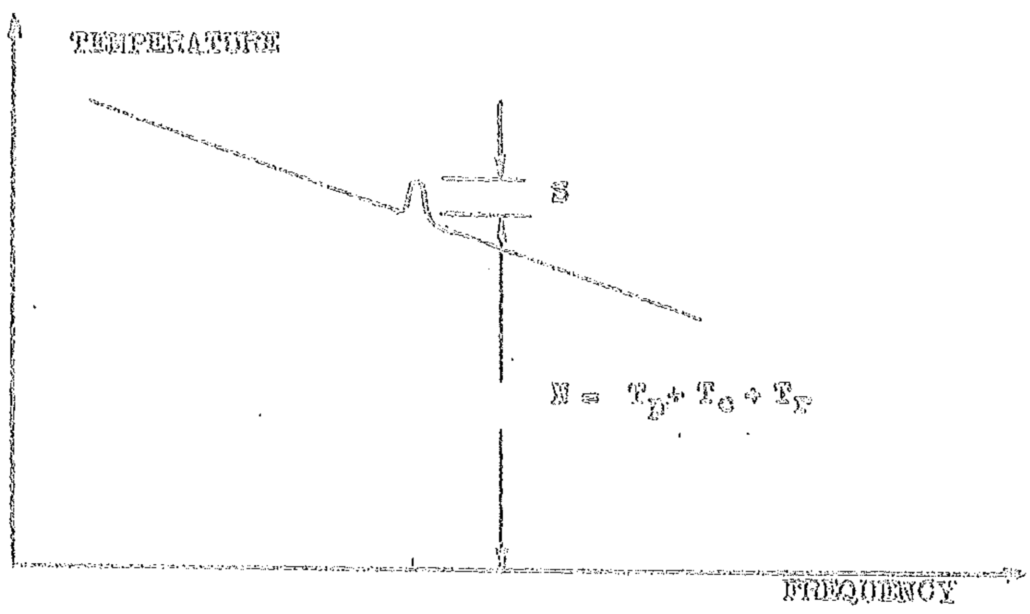


FIGURE 2 - The frequency spectrum of the expected radiation. S is shown here as an increase caused by emission but it may appear as a dip depending on the temperatures of the gas and the background. S will be much smaller than the diagram illustrates.

We wish to determine an expression for the peak signal-to-noise ratio, S/N, where S and N are defined in Figure 2. At the peak of the deuterium line we have:

$$\tau_p \approx \tau_c \approx \tau_d \ll 1. \qquad (3)$$

Since $\tau_d \ll 1$, we may approximate $1 - e^{-\tau_d}$ by τ_d and obtain

$$\frac{S}{N} = \frac{T_g - T_c - T_p}{T_r + T_c + T_p} \tau_d \qquad (4)$$

where we have included a term, T_r, which is the receiver noise temperature.

The S/N ratio given by Equation (4) can attain both positive and negative values depending, through T_c and T_p, as to where in the plane of the galaxy the antenna is directed. A negative value corresponds to net absorption of radiation by the gas and will result in a dip in the received noise spectrum at the line frequency. Analogously, a positive value of S/N corresponds to emission at the line frequency. Either measurement will serve to measure the deuterium-to-hydrogen abundance ratio. The conclusions as to effect of antenna direction, antenna size,* and receiver noise are quite different in the two cases and are summarized below.

---

*Antenna size refers to the diameter of a parabolic reflector.

Emission Spectrum

1. Antenna should be directed to a cold region in the plane of the galaxy where strong hydrogen emission has been observed; $T_p = 0$, $T_c \approx 80^{\circ}$.
2. S/N ratio is independent of antenna size for antennas larger than about 20'.
3. If the receiver noise is zero, the S/N ratio is equal to $.56T_d$. Extremely low noise receivers are required. A maser receiver noise temperature of 30° would reduce the above figure to $.40T_d$.
4. The bandwidth of the observed line will be about 4 times that obtained in the absorption spectrum. This will mean that an emission S/N is as good as an absorption S/N which is twice as large.

Absorption Spectrum

1. Antenna should be directed to the hottest region in the plane of the galaxy; i.e., either the center of the galaxy or the radio star, Cass A.
2. S/N ratio is dependent on antenna size through the point source contribution T_p. As $T_p + T_c$ becomes much greater than T_g and T_r, the S/N ratio approaches $1.0\ T_d$, and is independent of antenna size.
3. Receiver noise temperature, T_r, should be small compared to $T_p + T_c$. This requirement can be met by parametric amplifiers for antennas of 84' and larger or by crystal mixers and vacuum tubes for antennas of 140' and larger.

The general conclusion that may be made is that with 84' antennas available, the absorption measurement can give slightly better S/N ratio with less stringent requirements on receiver noise. Some numerical values of S/N are given in Table II.

A very likely spot for the absorption measurement is the direction of the radio star Cass A. This is the most intense point source at UHF frequencies and strong hydrogen absorption measurements have been made in its direction [10, 11]. On the basis of these measurements, the deuterium spectrum can be predicted and is given in Figure 3.

2.2 The Measurement Problem and the Wiener Theorem Approach

Basically, we wish to measure the magnitude of a small dip in the noise power spectrum of a Gaussian random process. The dip is of the order of 10^{-4} of the height of the spectrum and is about 3 kc. wide.

It has been shown* that, Δ, the R.M.S. fractional uncertainty (R.M.S. departure from mean divided by mean), of a measurement Δf, requires an observation time, T, as determined by the equation,

$$\Delta = \frac{c}{\sqrt{T \Delta f}} \qquad (5)$$

where c is a constant of the order of unity dependent (not radically) on the details of the measurement and definition of resolution. If we substitute, $\Delta f = 3$ kc., and require a Δ of 3×10^{-5}, we find that the required observation time is of the order of 5 days.

The above value of Δ represents the fluctuations due to having to measure an average of a random time function and, of

*This relation is derived by Strum (12) for various types of radiometers and it is shown in (13) to also apply to the autocorrelation digital processing type measurement.

TABLE II - EXPECTED SIGNAL-TO-NOISE RATIOS WITH VARIOUS RECEIVERS, ANTENNAS, AND DIRECTIONS

RECEIVER NOISE	ANTENNA DIAMETER	DIREC-TION	POINT SOURCE TEMP.	CONTINUOUS BACKGROUND TEMPERATURE	SIGNAL TO NOISE
T_r	-	-	T_p	T_c	S/N
0	INF.	(A)	10^8	125	1.0 T
30	250'	(A)	7300	125	.98 T
30	60'	(A)	420	125	.73 T
200	250'	(A)	7300	125	.95 T
200	140'	(A)	2400	125	.88 T
200	84'	(A)	820	125	.72 T
200	60'	(A)	420	125	.56 T
500	250'	(A)	7300	125	.92 T
500	140'	(A)	2400	125	.80 T
500	84'	(A)	820	125	.57 T
500	60'	(A)	420	125	.40 T
30	24' up	(B)	0	80	.40 T *
200	24' up	(B)	0	80	.16 T *
200	84'	(C)	500	300	.52 T
200	60'	(C)	250	300	.40 T

(A) CASSEOPEIA

(B) COLDEST REGION IN PLANE OF GALAXY

(C) CENTER OF GALAXY

Peak values of T are in the vicinity of 10^{-4}

* Emission profile - Profile will have greater bandwidth than the absorption profile by approximately a factor of 4. This will mean ½ the fluctuation at the output and means an emission S/N is as good as an absorption S/N which is twice as large.

	ANTENNA SIZE			
	250'	140'	84'	60'
MASER $T_r = 30^0$	4.4	5.1	6.0	8.0
PARAMETRIC AMPLIFIER $T_r = 200^0$	4.7	5.5	8.2	13.5
VACUUM TUBES AND CRYSTAL MIXERS $T_r = 500^0$	5.0	6.6	13.1	26.6

FIGURE 3 (a) - The number of days of required observation time is shown as a function of antenna size and receiver noise. The observation time is chosen so that the R.M.S. fluctuations are 1/8 of the peak of expected absorption in the Cassecopeia source assuming $n_d/n_h = 1/6700$. The longest observation time in previous attempts was 3/4 day. The limitations on observation time are the stability of the receiver and, of course, the availability of the antenna.

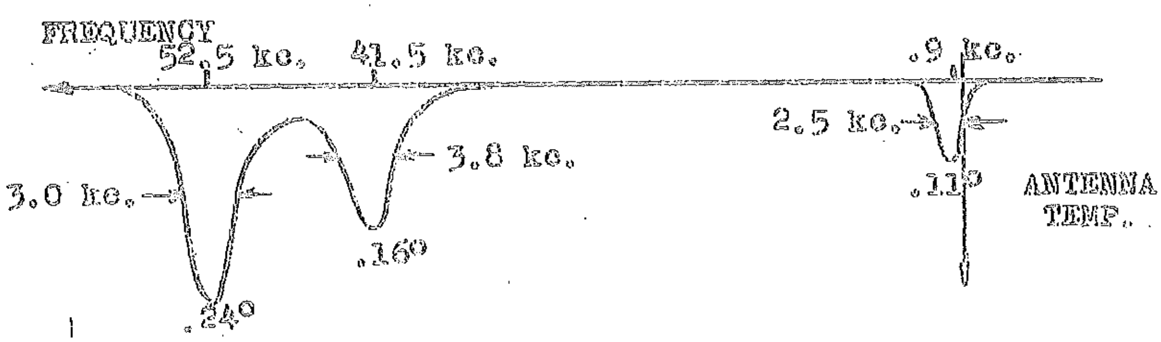


FIGURE 3 (b) - Expected deuterium profile for 1000° of background temperature (84' antenna) from Cassecopeia assuming $n_d/n_h = 1/6700$. The information was inferred from hydrogen absorption measurements reported in references (10) and (11). The frequency noted is the shift as referred to the local standard of rest.

course, does not include any error due to equipment instabilities. It is this problem of maintaining equipment amplitude stability of the order of 3×10^{-5} per day which is the present limitation on performing the deuterium line experiment. Since the stability of open-loop analog equipment rarely exceeds 10^{-3} per day, some type of feedback, comparison technique (since we wish to measure only the dip in the spectrum), or digital processing system is needed.

Three different radiometer systems are illustrated in Figure 4. Present day radio astronomy receiving apparatus is based on combinations and variations of the systems shown in the figure.

Receiving system A suffers from the fact that the receiver gain will fluctuate as the receiver is scanned, resulting in severe errors. System B attempts to overcome this difficulty by rapidly switching at the input between the spectrum to be measured and a reference flat noise spectrum *. The output of the system is responsive to the difference between the two signals and, to first order, receiver gain fluctuations cancel out. This type of radiometer has met with success in hydrogen line and galactic noise measurements but it is doubtful that the stability necessary for the deuterium line measurement can be achieved in this manner.

Of more direct interest is the system C, which uses a group of filters arranged to measure the spectrum at several adjacent points. The measurements are made at the same time using a common receiver (amplifier); thus, receiver gain fluctuations do not affect the measurement of the fractional dip in the spectrum.

---

*The switching can also be accomplished by switching the local oscillator frequency.

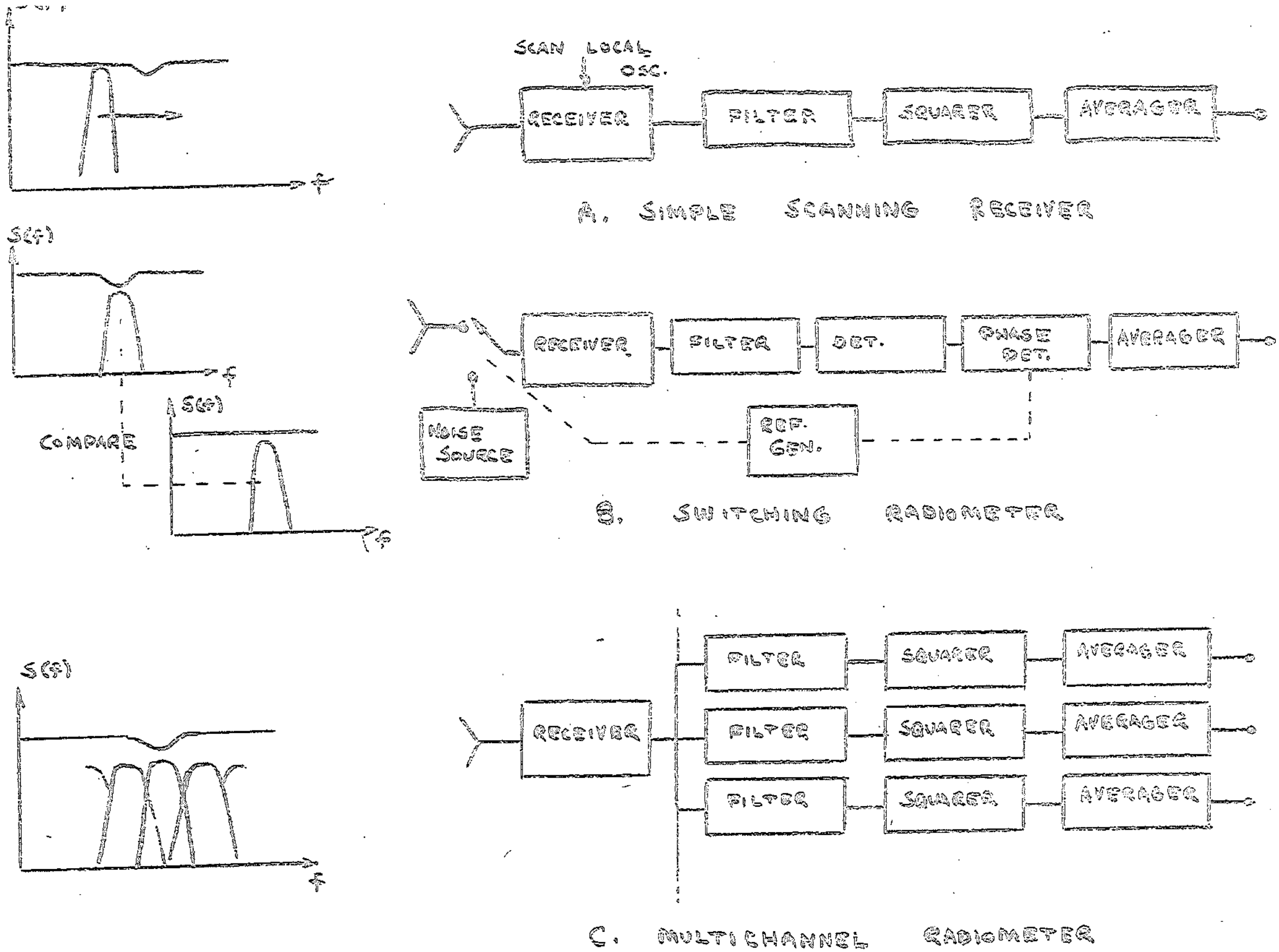


FIGURE 4 - TYPES OF RADIOMETERS

However, the individual filters must have extremely high stability, which is the main fault with this system. Even with temperature controlled crystal filters it is not known if the necessary gain stability of 3×10^{-5} per day can be achieved.

It is the basic proposal of this project that the filtering operation indicated in system C be performed digitally by the use of the autocorrelation function and the Wiener Theorem *. The advantage of this method is that the accuracy and stability are virtually unlimited.

It would be wasteful to go into a long discussion of the wonders of this type of analysis. An illustrative example, taken from Reference (13) is the following:

> "... we were able to discover in the general wave record a very low-frequency peak which would have surely escaped our attention without spectral analysis. This peak, it turns out, is almost certainly due to a swell from the Indian Ocean, 10,000 miles distant. Physical dimensions are: 1 mm high, a kilometer long."

Briefly, the Wiener Theorem states that under appropriate, quite general, conditions the power spectral density, $S(f)$, is given by

$$S(f) = \int_{-\infty}^{\infty} R(T)\, e^{-j\omega T}\, dT \qquad (6)$$

where $R(T)$ is the autocorrelation function of the time function, $X(t)$, and is given by

---

*An introduction to spectral analysis is given in (14). A detailed reference, pertinent to the problem, is (13).

$$R(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} X(t)X(t+\tau)\, dt \qquad (7)$$

The fact that the time function is only measured for a finite time has the following effects which are treated in (13):

1. $R(\tau)$ can only be specified for $\tau \leq \tau_M$. Roughly, this has the effect of limiting the frequency resolution of the measurement of $S(f)$ to $\Delta f = 1/\tau_M$.
2. We cannot allow T to approach infinity in Equation(7). This has the effect of producing Equation (5), where $C = 1$.

Since digital processing of the data is to be used, two additional modifications need to be made:

3. $X(t)$ will be sampled at discrete times. This effect is treated in (13) and no serious modifications occur, provided the sampling rate is fast enough.
4. The samples of $X(t)$ must be quantized. This topic has not been theoretically investigated except in a few scattered cases, and will form a major part of the theoretical work in connection with this project. Remarkably, it is very likely that the time function can be quantized into just two values and the true spectral density can be determined from the autocorrelation function of this drastically quantized signal. This topic is discussed in Section 5.

2.3 System Block Diagram

The block diagram of the receiver and correlator to be presented in this section and the next are the result of a preliminary examination of the system requirements. Their purposes are to show that reasonable solutions of the system requirements exist, and to give an estimate of the cost of the system. It is felt that additional time, of at least six weeks, should be spent investigating the detection system before beginning development of equipment.

The most difficult problem in the receiver development is the very stringent requirement on bandpass stability. The digital processing system eliminates any direct requirement on gain stability, but does not eliminate the second-order effect of differential gain fluctuations at two frequencies in the bandpass. Specifically, the requirement is that the gain at one frequency shall not change with respect to the gain at another frequency 10 kc. away by more than a part in 10^5 per day.

It is worthwhile to go through a simple calculation which will show that the bandpass stability requirement is reasonable, but that special techniques such as temperature control will be necessary. Suppose we calculate, α, the differential change in power gain for two frequencies, spaced Δf apart, in the bandpass of a single tuned circuit of bandwidth, BW, centered at frequency f_0. In terms of the fractional change of capacitance and inductance, dC/C and dL/L, we find,

$$\alpha = \frac{4 \Delta f\, f_0}{(BW)^2} \left(\frac{dC}{C} + \frac{dL}{L} \right) \qquad (8)$$

Thus, if we make the tuned circuit very wide band compared to Δf, the component stability requirements are reduced. Assume 10 single tuned circuits, $\alpha = 10^{-6}$ per circuit, $\Delta f = 10$ kc, $f_0 = 30$mc and BW = 10 mc. We find that $dC/C + dL/L = 10^{-4}$ is required. The temperature coefficient of the most stable capacitors and inductors is of the order of 10^{-4} per degree. (A "zero" temperature coefficient capacitor is zero $\pm .5 \times 10^{-4}$.) Thus, by temperature control of the order of a degree, and by trying to compensate inductance changes with capacitance changes, it should be possible to achieve the desired stability.

A way of measuring the bandpass stability is indicated in Figure 5. This measurement system offers interesting possibilities since, if the changes in bandpass can be measured, they can be corrected by a servo loop.

A block diagram of a possible system is given in Figure 6, and component costs are listed in Table III. A few of the pertinent details will be discussed.

A first I.F. frequency of 35 mc. is chosen to give good image rejection and also, in lieu of 30 mc., to avoid 10 meter amateur band interference which has been bothersome at radio astronomy installations. The second I.F. of 10.7 megacycles is chosen because of the availability of inexpensive crystal filters at this frequency. Both I.F. amplifiers will be about 10 mc. wide. The

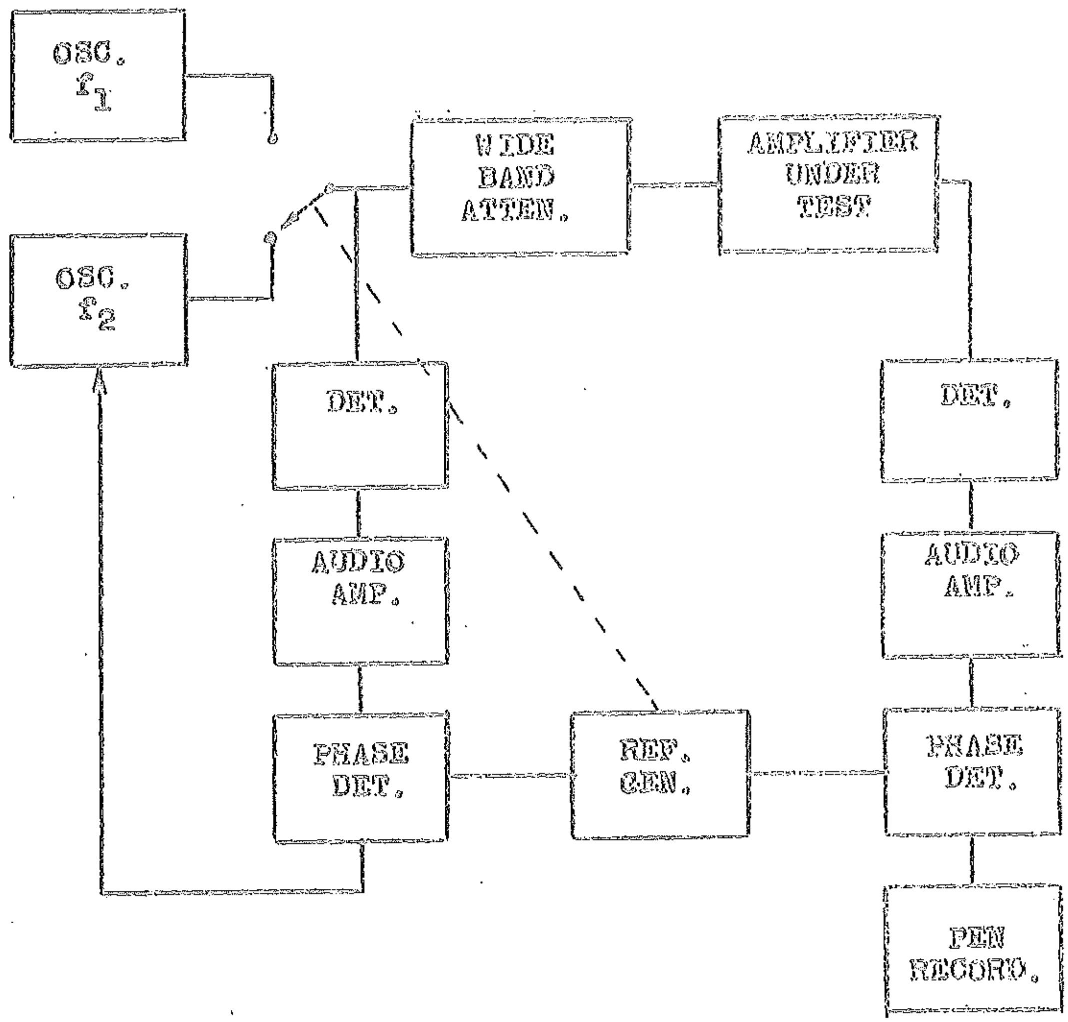
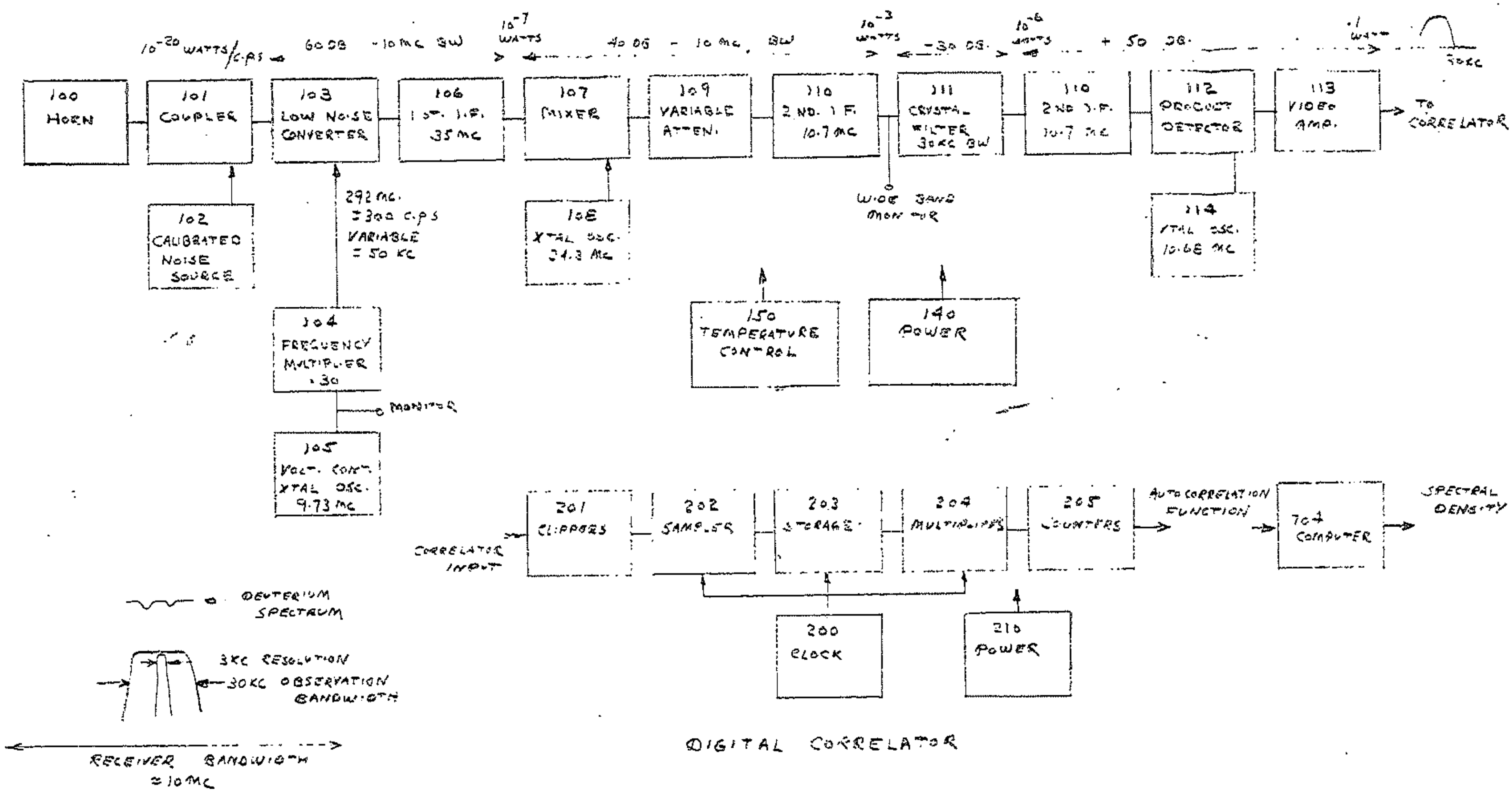


FIGURE 5 - The above system measures the difference in gain of an amplifier at frequencies f_1 and f_2. The phase detector at the input corrects the amplitude of oscillator f_2 so that it is equal to the amplitude of oscillator f_1. The second phase detector detects the difference in amplitude at the output of the amplifier. If the output of this second phase detector was applied to a correcting device the bandpass of the amplifier would be automatically stabilized.

DEUTERIUM LINE RECEIVER



DIGITAL CORRELATOR

S. WEINREB
4/13/60

observation bandwidth of 30 kc. is determined by a highly stable crystal filter.

Before constructing the receiver, an interference study will be made in the vicinity of 327 mc. If strong interfering signals are near this frequency, it would be desirable to have more selectivity near the input of the receiver to keep the interference from overloading the I.F.

Unit 102, the calibrated noise source, is necessary to measure galactic noise temperature, and is also of use to measure receiver noise. The first local oscillator is variable over a small range to follow seasonal doppler shifts of the deuterium line frequency.

The I.F. and video portions of the receiver will be transistorized and designed to give the utmost in bandpass stability. It is felt that the temperature-controlled transistor amplifiers will have higher stability than tube amplifiers. Zener reference elements will be used to stabilize the DC voltages.

A most critical and difficult part of the receiver is unit 103, the low noise converter. If the receiver is to be used with an 84' dish, the noise figure should be under 3 dbs. A parametric amplifier could easily meet this requirement, but is likely to have poor bandpass stability. The parametric amplifier will be of the up-converter type, and will necessitate a frequency and gain stabilized pump source. An alternate approach would be to cool a wideband crystal mixer to liquid nitrogen temperatures. This device

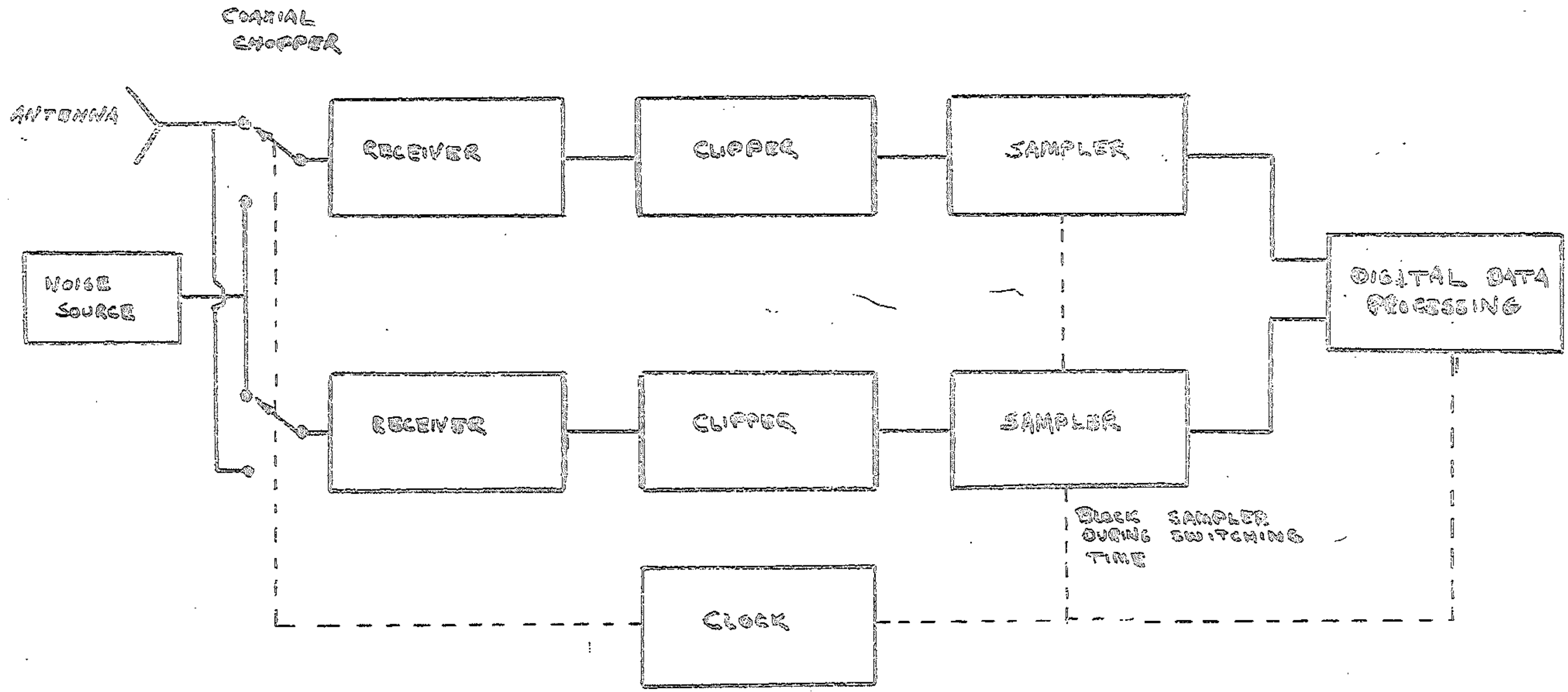


FIGURE 7 - AN ALTERNATE SYSTEM - THE OUTPUT OF THE SYSTEM IS THE DIFFERENCE BETWEEN THE POWER SPECTRUMS SEEN BY THE ANTENNA AND THE NOISE SOURCE. NO ERROR WILL BE CAUSED BY GAIN, BANDPASS, OR CHOPPER DWELL TIME FLUCTUATIONS.

should have good bandpass stability, but it is unknown if the noise figure requirement can be met. Vacuum tube amplifiers, using tubes such as the 416B, 6299, or 7077 do not quite achieve the noise figure requirement, but their use will be considered.

The temperature control mechanism must meet the requirement of keeping all parts of the critical equipment to $\pm 1^{\circ}$ for a period of many days. Depending on the bulk of the equipment, this may require several independent servo loops, but the problem should not be too difficult.

An alternate approach to the receiver problem is shown in Figure 7. This system makes a comparison between the signal and a flat noise spectrum and eliminates the need for high bandpass stability in the receiver. This switching radiometer fits in very nicely with the autocorrelation processing and actually reduces the amount of digital data handling which is required. A tabulation of the cost has shown that it will be the same as for the first system. Two receivers are needed but high bandpass stability is not required and the correlator is not as expensive. A final decision on the type of system will require more study.

2.4 The Digital Correlator

The first question which should be answered is, "Why not use a high-speed digital computer to perform the correlation?". The answer is that it would take too much computer time. If 30 kc. information is to be correlated and give 3 kc. spectral resolution approximately 10^6 multiplications per second must be performed. The IBM 704 computer can perform 5×10^3 36 bit multiplications per second, thus the information would have to be stored and slowly fed to the computer. For 5 days of observation time, 1000 days of computer time would be needed.

The answer to this problem is to design a specialized digital machine which has 20 multipliers, each having only sufficient bit capacity to give the desired accuracy. It is not difficult to develop a machine which can perform the entire autocorrelation operation in real time and thus eliminate the need for extensive information storage capability.

As stated in Section 3, the theoretical problem of estimating the spectral density from a knowledge of a finite number of samples of the time function is one which is solved for the purpose of this project. A few pertinent references on this problem are (13), (15), and (16). However, the problem of studying the effect of quantizing the samples into digital form is one that is unsolved.

A plausible guess as to the fineness of the quantization is found by setting the quantization error equal to the desired accuracy in the spectral density. However, experimental results obtained on the Whirlwind computer in reference (16) show little change in the spectral density as the quantization coarseness is increased. In fact, little change occurs when the signal is quantized into just two levels. The quantization into two levels (positive and negative) is particularly easy to instrument and is the same as severe clipping of the time function.

A procedure for obtaining the exact spectral density of a Gaussian random process from the one-bit quantized time function is suggested by the following relation first derived by Van Vleck (17),

$$\rho_x(\tau) = \sin\left[\frac{\pi}{2}\ \rho_y(\tau)\right] \qquad (9)$$

where $\rho_x(\tau)$ is the true normalized autocorrelation function of a Gaussian random process and $\rho_y(\tau)$ is the normalized autocorrelation function of the one-bit quantized process.

The procedure suggested by Equation (9) is as follows:

1) Severely clip the time function.

2) Sample this clipped time function so that each sample is a single bit of information.

3) Perform all of the operations of autocorrelation (easily) on the one-bit samples.

4) Multiply the resulting autocorrelation function by $\pi/2$ and take the sine of the result on a computer to give the autocorrelation function of the unclipped time function.

5) The autocorrelation function is now Fourier transformed on a computer to give the spectral density. Little computer time is necessary to perform this operation.

Equation (9) is applicable to Gaussian signals only. It is quite reasonable to postulate that the incoming signal is Gaussian; we should try to preserve this Gaussian characteristic in the detector of the receiver. For this reason the product detector is used.

Equation (9) is not the entire story, however, because it applies to the true autocorrelation function and not to the measured (finite time) autocorrelation function. However, preliminary results have indicated that the procedure of one-bit correlation will be applicable and further work will be done in this direction.

A pertinent discussion of the construction of digital correlators is given in References (16) and (18). A block diagram of a one-bit correlator is given in Figure 8.

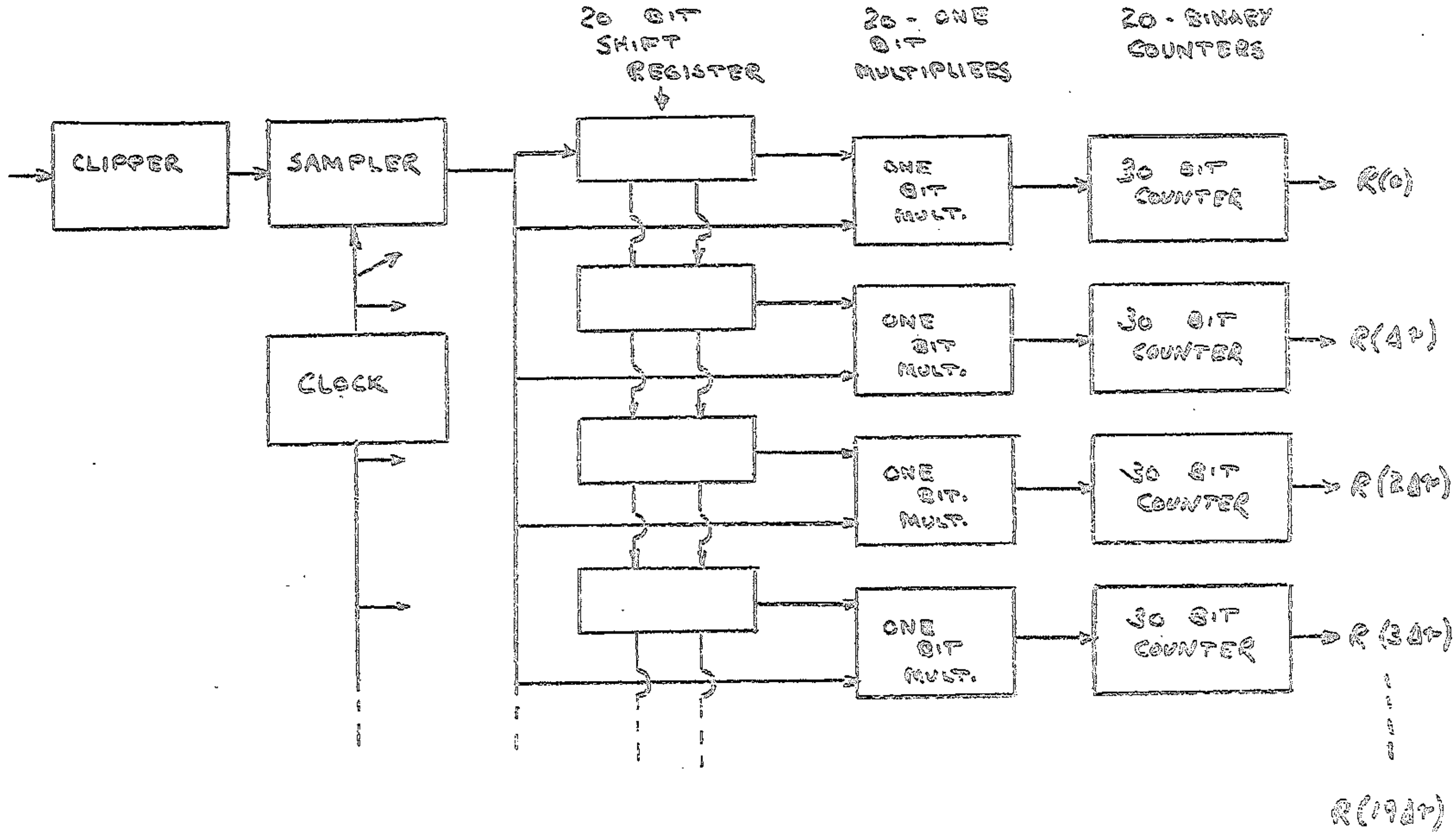


FIGURE 8 - DIGITAL CORRELATOR

The desired starting date of the project is June 1, 1960 or as soon as possible after this date. It is intended that the research encompass a period of eighteen months.

The first month of the project will be spent in theoretical study to determine an optimum system and also to allow time for delivery of the first pieces of equipment. This will be followed by eight months development work on the receiver and correlator. Approximately half of the units comprising the receiver will be purchased; the remainder will be constructed. Most of the correlator will be assembled using commercially available "digital building blocks". The majority of contract purchases will be made in the initial nine-month period. finish Aug 1

July 1
Aug 1

Approximately four months time will be spent testing the system in the laboratory. At the end of this period the equipment will be moved from M.I.T. Research Laboratory of Electronics to a small 24' antenna operated by Harvard University at Harvard, Massachusetts. It is felt that it would be wise to test the system on this smaller antenna before taking up valuable time on a larger dish. When the system is operating satisfactorily, it will be moved to a 60' or larger dish antenna. A few such antennas exist in the vicinity of Cambridge.

The choice of observation antenna cannot be made at present. The decision depends on the following factors:

1. Priority of program in process at antennas under consideration.
2. Results of an interference study.
3. Noise and stability characteristics of the completed system.
4. Dates of completion of new antennas under construction.

The faculties of the M.I.T. electrical engineering department and Harvard astronomy department are, of course, available for consultation in specialized areas of the research.

Laboratory space, test equipment pool, shop facilities, and other service functions are available at the M.I.T. Research Laboratory of Electronics. An IBM 704 computer is available at M.I.T. and will be used in the research. Harvard University operates 24' and 60' antennas which will be available for the research, although, as previously mentioned, a larger antenna may be used for observations.

4.0 Personnel and Facilities

The project will be undertaken as a doctoral thesis by Mr. S. Weinreb, and will be under the guidance of Prof. J. B. Wiesner, Prof. A. G. Bose, and Prof. A. H. Lilley, who are members of the doctoral thesis committee. Short biographical sketches of these people are as follows:

Professor J. B. Wiesner, director of the Research Laboratory of Electronics and acting head of the Department of Electrical Engineering at M. I. T., was born in Detroit, Michigan in 1915. He received the B.S., M.S., and Ph.D. degrees from the University of Michigan in 1937, 1938, and 1950, respectively. As a member of the Radiation Laboratory, the M. I. T. faculty, and various governmental committees, Prof. Wiesner has been an outstanding leader in the fields of communication science, engineering education, and technology related to the defense of our country. He received the President's Certificate of Merit in 1948 and is a fellow of the American Academy of Arts and Sciences and the Institute of Radio Engineers.

Prof. Wiesner is particularly well suited to guide this project in that he is quite familiar with modern statistical communication theory and also has maintained an active interest in radio astronomy.

Professor A. G. Bose, assistant professor of Electrical Engineering, M. I. T., was born in Philadelphia, Pa., in 1929. He received the B.S., and M.S. degrees from M. I. T. in 1952 and the Sc.D. degree in 1956, all in Electrical Engineering. For the year 1956-57, Dr. Bose studied and taught in India under a Fullbright fellowship. Also in 1956, he was appointed assistant professor of Electrical Engineering at M. I. T. Professor Bose's doctorate thesis was entitled "A Theory of Nonlinear Systems" and he has been actively concerned with teaching and research in statistical communication theory for the past several years.

Prof. Bose's knowledge in this field will be a valuable aid to the data processing aspect of the research.

Professor A. E. Lilley, associate professor of Astronomy, Harvard University, was born in Mobile, Alabama in 1928. He received his B.S. and M.S. degrees in Physics at the University of Alabama, and the Ph.D. in Astronomy at Harvard University. From 1954 to 1957, Dr. Lilley was with the radio astronomy group at the Naval Research Laboratory, were he did research on hydrogen absorption lines and various other radio astronomical problems. In 1957, he was appointed assistant professor of Astronomy at Yale University and, in 1959, associate professor of Astronomy at Harvard College Observatory and director of Agassiz Station Radio Astronomy Laboratory. He is a member of various astronomical societies, an Alfred P. Sloan Research Fellow, and is the recipient of the Bart J. Bok prize from Harvard University in 1958.

Prof. Lilley's very pertinent work on hydrogen absorption line observations and his knowledge of the present state of the art in radio astronomy assure that his help will be a valuable aid to this project.

Mr. S. Weinreb was born in New York, New York, on December 9, 1936. He received the B.S. degree in Electrical Engineering in 1958 at M. I. T. where he was the recipient of Boston Section IRE Student Award to the most outstanding E. E. senior. During 1958-59 he did teaching and research at M. I. T. which resulted in the publication of a paper in Proc. IRE concerning nonlinear reactance frequency multipliers. He pursued full time studies at M. I. T. during 1959-60 under a National Science Foundation graduate fellowship. He was engaged in part time employment with Raytheon Mfg. Co., Radiation Inc., and the Ewen Knight Corporation doing work in communication receiver, parametric amplifier, and radiometer development. While at Ewen Knight he was responsible for the development of a hydrogen line radiometer for Harvard Observatory.

5.0 **PROPOSED BUDGET**

TO DETECT THE GALACTIC DEUTERIUM LINE

For 18 Month Period June 1, 1960 - November 30, 1961

Salaries & Wages		
1 Graduate Student - Part time	$6,300	
1 Technician - Full time	7,200	
1 Technician and/or Machinist-1/3 time	2,500	$16,000
Travel		1,000
Daily trips by auto by 1 or more personnel for about 6 months or more between Cambridge, Mass. and Harvard, Mass.		
Materials & Services		30,400
(See Table III attached)		
Other Direct Charges		200
Communication & Shipping Charges		
Employee Benefits		2,400
Including Pensions, Social Security, Blue Cross, and Vacation Allowances at 15 per cent of Salaries and Wages		
Total Direct Costs		$50,000
Indirect Costs (20 per cent of Total Direct Costs)		10,000
Total Estimated Costs		$60,000

TABLE III

EQUIPMENT COST

Unit Numbers	Description	Component Cost Estimate	Comments
100	Antenna Feed	$ 1500	Jasik Labs.
101	Directional Coupler	$ 145	H. P.
102	Calibrated Noise Source	$ 500	A.I.L. or Kay Electric
103	Low Noise Converter	$ 5000	Stabilized Parametric Amplifier
104	Frequency Multiplier	$ 300	Construct
105	Volt. Controlled Xtal. Osc.	$ 550	Bulova Watch Co.
106	1 ST. I.F.	$ 500	Construct
107	Mixer	$ 55	Construct
108	Xtal. Osc.	$ 100	James Knights Co.
109	Variable Attenuator	$ 100	Jerrold Co.
110	2nd I.F.	$ 400	Construct
111	Xtal. Filter	$ 100	Bulova Watch Co.
112	Product Detector	$ 50	Construct
113	Video Amplifier	$ 150	Construct
114	Xtal. Osc.	$ 100	James Knights Co.
140	Power Supplies	$ 1000	2 - Transistor Supplies 2 - Tube Supplies
150	Temperature Control of Receiver	$ 1500	Includes packaging of receiver

TABLE III

EQUIPMENT COST (continued)

Unit Numbers	Description	Component Cost Estimate	Comments
200	Clock	$ 200	Construct
201	Clipper	$ 300	Construct
202	Sampler	$ 200	Construct
203-210	Logic Circuitry for Correlator	$15000	Have built commercially
Special Test Equipment			
	Bandpass Stability Test Set	$ 700	Construct (See Fig.5)
	Precision Sweep Generator	$ 850	Kay Electric
	Interference Field Intensity Measurement Set	$ 1100	
	TOTAL	$30,400	

6.0 BIBLIOGRAPHY

1. I. S. Shklovsky, Astr. Zhur., vol. 29, p. 144; 1952.

2. L. Heller, "Theories of Element Synthesis and the Abundance of Deuterium," Astr. J., vol. 126, pp. 341-355; September, 1957.

4. G. G. Getmanzev, K. S. Stankevitch, and V. S. Troitsky, "Detection of Monochromatic Radio Emission of Deuterium from the Center of the Galaxy on a Wavelength of 91.6 cm," Dok. Akad. Nauk USSR, vol. 103, pp. 783-786; February, 1955.

5 4. G. J. Stanley and R. Price, "An Investigation of Monochromatic Radio Emission of Deuterium from the Galaxy," Nature, vol. 177, pp. 1221-1222; June 30, 1956.

6 5. R. L. Adgie and J. S. Hey, "Intensity of the Radio Line of Galactic Deuterium," Nature, vol. 179, p. 370; February, 1957.

7 6. R. L. Adgie, "An Attempt to Detect the 327 MC/S Line of Galactic Deuterium," Paris Symposium on Radio Astronomy, pp. 352-354; Stanford Press, 1958.

8 7. S. Weinreb, "The Detection of UHF Radiation from Deuterium in Interstellar Space," B.S. Thesis, M.I.T.; June, 1958.

8. J. L. Pawsey and R. N. Bracewell, "Radio Astronomy," Oxford University Press; London, 1955.

9. G. B. Field, "Excitation of the Hydrogen 21-cm. Line," Proc. I.R.E., vol. 46, pp. 240-250; March, 1952.

10. J. P. Hagen, A. E. Lilley, and E. F. McClain, "Absorption of 21 cm. Radiation by Interstellar Hydrogen," Astrophys. J., vol. 122, pp. 361-375; November, 1958.

11. C. A. Muller, "21 cm. Absorption Effects in the Spectra of Two Strong Radio Sources," Astrophys. J., vol. 125, pp. 830-834; May, 1957.

12. P. D. Strum, "Considerations in High Sensitivity Microwave Radiometry," Proc. I.R.E., vol. 46, pp. 43-53; January, 1958.

13. R. B. Blackman and J. W. Tukey, "The Measurement of Power Spectra," Dover Press; New York, 1958.

14. W. B. Davenport and W. L. Root, "Random Signals and Noise," McGraw-Hill; New York, 1958.

15. J. J. Faran and R. Hills, "Correlators for Signal Reception," Acoustics Research Lab., Harvard Univ., Tech. Memo. No. 27; September, 1952.

BIBLIOGRAPHY (CONTINUED)

16. J. F. Kaiser and R. K. Angell, "New Techniques and Equipment for Correlation Computation," Servo. Lab., M.I.T., Tech. Memo. No. 7668-TM-2; December, 1957.

17. J. H. Van Vleck, "The Spectrum of Clipped Noise," Radio Res. Lab. Report No. 51, Harvard Univ.; July, 1943.

18. C. R. Green, "Measurement of Polarity Coincidence Correlation Functions Using Shift Register Elements," Nav. Ord. Lab. Report No. 4396; December, 1956.