National Radio Astronomy Observatory
Tucson, Arizona

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MEMORANDUM

To: 12 m Memo Series

From: P. R. Jewell

Subject: Continuum Digital Backend

I. Introduction

The NRAO has developed a continuum digital backend (DBE) as a replacement for the analog standard backend (SBE) in use at the 12 m site for nearly 20 years. The DBE offers numerous advantages over the SBE, including more precise and more accurately calibrated data. Whereas the SBE produces simply a switched power or total power signal, the DBE simultaneously records four raw switch phases, two of which can contain the emission from a synchronous calibration source such as a noise tube. In addition, all data are recorded in double precision (32 bit) rather than single precision numbers. Finally, the DBE digitally blanks the incoming signal during subreflector movement.

The DBE is a general purpose continuum backend to be used for all standard continuum observing programs, including ON/OFF measurements and dual beam mapping. As the DBE supercedes the SBE in virtually all respects, we will no longer support the SBE for data-taking by observers. In the short term, the SBE will continue to drive the on-line chart recorders.

In the material below, we discuss the principles of operation, hardware setup, the control system software setup, data calibration, and data analysis for the DBE. This memo is intended to acquaint both observers and the NRAO staff with the operation of the DBE.

II. Principles of Operation

A block diagram in the DBE and associated telescope electronics is given in Figure 1. The DBE is a 2 channel, 4 phase continuum signal processor. After analysis processing, DBE data results in both switched power and total power signals and can be used with the subreflector (or beam switcher) switching or fixed. If a calibration noise tube is available, its signal can be

recorded as one of the switch phases. The four phases of the DBE
are defined as

$$\Phi_1 = SIG + CAL , \qquad (1)$$
$$\Phi_2 = REF + CAL , \qquad (2)$$
$$\Phi_3 = SIG , \qquad (3)$$
$$\Phi_4 = REF . \qquad (4)$$

The signals that can be computed from these phases are

switched power $\quad SP = (\Phi_1 - \Phi_2 + \Phi_3 - \Phi_4)/2 , \qquad (5)$
total power $\quad\quad TP = (\Phi_1 + \Phi_2 + \Phi_3 + \Phi_4)/4 , \qquad (6)$
cal signal $\quad\quad\;\; C = (\Phi_1 + \Phi_2 - \Phi_3 - \Phi_4)/2 , \qquad (7)$
zero level $\quad\quad\;\; Z = \Phi_1 - \Phi_2 - \Phi_3 + \Phi_4 . \qquad (8)$

The DBE has three front panel digi-switch controls, labeled

S/R   DELAY 1   DELAY 2

S/R controls the subreflector switching period. At present,
S/R must always be set to 0.25 sec (a 4 Hz switch rate), so that
the FORTH control computer can acquire data in synchronism with its
basic cycle time.

DELAY 1 is used to set the blanking interval so that no signal
is accumulated while the subreflector is in motion between
positions. DELAY 1 is typically set to 28.0 ms.

DELAY 2 is used to delay the start of blanking for an interval
after the sig/ref pulse change so as to compensate for mechanical
inertia of the subreflector (the subreflector requires a few
milliseconds to begin its motion after the switch signal is
received). DELAY 2 is calculated from the formula

DELAY 2 = [S/R]/2 - [desired delay in start of blanking].   (9)

The desired delay is typically about 9 ms, so for [S/R] = 250 ms,
DELAY 2 = 116 ms.

III. Hardware Setup for the Digital Backend

The hardware cabling setup is given in Figure 2. In general,
these cables will be in place. If any cables have been removed,
perhaps for use of the SBE or a special backend, the telescope
operator should check the following three items, in particular:

(1) Insure that the DBE is in series with the cal signal from
the computer. Bit 8 from the computer should go to CAL
IN on the DBE, and CAL OUT on the DBE should go to the

CAL jack on the back of the subreflector control box. These cables are loose behind the computer rack and are labeled.

(2) On the back of the subreflector control box, switch the cal synchronization switch to the "DBEND" position.

(3) On the subreflector Switch Rate Generator box, attach the BNC cable labeled "Digital Backend" to the external jack and turn the knob to EXT.

Note that if spectral line beam switching is being done, the cable connected to the external switch rate jack will be from the 512 channel Multiplexer. Take care to remove this cable and attach the one from the DBE.

IV. Software Setup in the FORTH Control Computer

The data-taking program in the FORTH computer is called DBE. This program should be loaded (by the operator) instead of TWO, which was formerly used for the SBE. In other words, when switching from SPECTRA to digital backend data-taking, simply type DBE. When rebooting, type

3 LOAD 12M TRACK DBE.

The setup for the DBE is much the same as for TWO, but with several important exceptions, particularly concerning data calibration and the length of scans:

(1) In general, do not enter values for #C and #CP. Instead, enter values for NT and DSF. NT indicates whether noise tube emission is part of the switch cycle; it is set to 0 (zero) for no noise tube and 1 if a noise tube exists. DSF is the Data Scale Factor and is used only if there is no noise tube (NT = 0). The DSF factor is used by VAX analysis procedures to scale the raw DBE numbers, which are of order 10^5, to numbers that are easier to display (more information of calibration is given in Sections V and VI). In the control system, NT corresponds to #C and DSF to #CP and appear under those headings on the status monitor. If, for some reason, the observer wants different values of DSF in the two receiver channels, they can be entered with the old #CP, #CP 1+ commands.

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A typical value for DSF is 10000. The formats for entering these parameters are

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n NT             where n is 0 or 1 ;
mmmmm DSF        where mmmmm can be any number between 1
                 and 32768.
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Note that there are no "stores" (!) at the end of these commands. These command set NT and DSF for both receiver channels. The values of TC can be used to change data scaling.

(2)   The minimum length of a sample (set by the SEC command) is 0.5 s. A sample of this minimum length will consist of a single four phase cycle of 0.125 s phases. (The minimum length of a SBE sample was 0.1 s.)

(3)   The maximum number of ON/OFF repeats (RPTs) in a scan, where a repeat is an OFF-ON-ON-OFF sequence, is 48. The maximum number of mapping points in a dual or single beam map is 192 per scan (row).

(4)   The data-taking modes LS, BS, SPDATA, and TPDATA do not affect DBE data and need not be set. However, if the subreflector action is inconsistent with the value of SPDATA and TPDATA, an error message will be printed on the FORTH console.

(5)   The value of UNIT does not affect DBE data scaling.

(6)   The basic observing commands such as SEQUENCE, AROW, FOCALIZE, FIVE, etc., are the same as in TWO. There is no longer a procedure for a separate noise tube calibration scan as the calibration is done as one of the switch phases whenever a noise tube is present.

(7)   DBE data is not recorded on the FORTH tape or data disk. Thus, for continuum observing runs, the operator should make a backup tape copy of the VAX PDFL file as soon as possible after the run.

In addition to the normal continuum setup parameters, the information that the observer should give the operator are (1) the values of TC (for each channel) and (2) the value of DSF. In general, the default value of DSF (10000) should be used. If a noise tube exists, TC should be the temperature of the noise tube. The temperature can be measured with HOT/COLD loads (see Section V). If there is no noise tube, the values of TC can be adjusted by observing a calibration source of known flux density. A noise tube is generally available for observations at 3 mm wavelength but not for 1 mm or shorter. As always, a value of ATTN (the atmospheric zenith optical depth) must be measured from a tipping scan.

The control computer issues the signal to the DBE to begin a cycle of four phases. Each time a cycle is completed, the contents of the four phase registers are dumped to the control computer. Ideally, this occurs every 500 ms of elapsed time. The presence of error conditions (loss of phase lock or pointing out of tolerance) may cause the elapsed time to exceed the specified integration time. If an error condition is detected during Phases 1 or 2, a restart signal is sent to the subreflector and the phases are retaken. If the error condition occurs during phases 3 or 4, the entire 500 ms of data are rejected. The control system time counter counts down monotonically in 100 ms intervals (the monitor updates only every second). If the cycle must be retaken after reaching Phases 3 or 4, the scan time counter on the status monitor will indicate that the integration has proceeded farther than it really has (the counter cannot be reset backwards in time). This can lead to the peculiar situation of the time counter running to negative values at the end of the scan. The correct amount of data is always recorded, however.

At the end of each scan, the data stored in the FORTH buffers is transmitted to the data file on the VAX for analysis. The numbers transmitted and stored on the VAX are completely raw numbers; no calibration or scaling of any kind have been applied. The values of TC and DSF entered into the control system are used only for header documentation. Analysis routines use these parameters to scale the data.

V. Data Calibration

The calibration scale of DBE is determined by the values of TC (and DSF, when no noise tube is present). The observer has two options for determining a proper value for TC:

1. The Relative Method. Measure a standard source and adjust TC to give the correct temperature. The flux density scale is determined by TC and the aperture efficiency value, set in the control system by %EFF.

2. The Absolute Method. Perform a HOT/COLD load to set the the temperature scale absolutely. The aperture efficiency can be measured on a standard source or taken from values supplied by the Observatory staff.

The relative method is usually the easiest, provided that a good calibrator source is available. To use the absolute method, follow this recipe:

The operator should

    a)   Drive the telescope to the zenith and open the door to 90°.

    b)   Set up a scan with the parameters

          EXPEDITE
          0 ATTN !
          20 SEC !
          30 RPT !
          (lock subreflector)

The operator or observer must take hot and cold loads onto the telescope and alternately hold them above the receiver box. The vane absorber mounted in or above the receiver will usually suffice as the hot load. When the loads are ready, proceed as follows:

    c)   Start the scan with the command

          1 SEQUENCE

    d)   As the first stage of the scan, switch the I.F. attenuator switches on the continuum rack to over 100 dB by switching from 0 to 1 in the first digit of the thumbwheel switches. This will establish the zero level of the system. After 10 – 20 seconds, return the switches to their original settings.

    e)   Next, alternately switch the hot and cold loads in for two or three repetitions, of 10 – 20 sec per cycle.

    f)   Next move all loads from the receiver so that only the sky is seen. If a noise tube is available, switch it on for one or two repetitions (sky and noise tube).

The total length of the scan specified above is 4 min. If you need more time, set RPT to a larger number (say 40).

A procedure called HC is available to reduce the scan. To use the procedure, initiate CONDAR and type

    INSTALL HC

Start the procedure by typing

    scan# HC

and you will be prompted for input data. Alternatively, you can make the computations by hand by typing

scan# T TABLE

The formula for computing new TC values is

$$TC_{new} = \frac{T_{hot} - T_{cold}}{TA_{hot} - TA_{cold}} \, TC_{old} \, , \qquad (10)$$

where T_{hot} is the ambient temperature and T_{cold} is usually 80 K (the liquid nitrogen temperature at the elevation of the telescope). TA_{hot} and TA_{cold} are the antenna temperatures of the hot and cold loads, respectively.

Neither the DBE integrators nor the control computer normalize the integration time with respect to time lost to blanking. In other words, the integration time is assumed to be [S/R]/2 per phase. If the calibration scale is set by integrations on hot/cold loads, this effect will be calibrated out.

VI.   Data Reduction

A.   POPS/CONDAR:

The data sent from the control computer and recorded on the VAX contains the four phases, integrated over the number of dumps, for each sample or sky position. Thus, the raw data scan contains four times as many points as there were samples. If the sample number is denoted by S_i and the phases in that sample as ϕ_i, the data are recorded in the order

S_1,ϕ_1 S_1,ϕ_2 S_1,ϕ_3 S_1,ϕ_4 S_2,ϕ_1 S_2,ϕ_2, S_2,ϕ_3 S_2,ϕ_4 ...

and so on. To obtain a table of these data, enter the CONDAR data reduction system and type

scan# GET TABLE .

Do not try to display these data with the PAGE SHOW command as the magnitude of the data are of the order 10^5 and will cause overflows on the display. These data are completely raw, with no calibration factors applied nor DC offsets subtracted.

Several new CONDAR verbs have been defined for the calibration and manipulation of DBE data. These are

FIXDBE   (calibrates the data and reorders it from sequential
           phases to sequential switched power, total power,
           calibration values, and zeroes);

SWITCHED   (reorders the data array to contain only calibrated
                switched power data);

TOTALPWR   (reorders the data array to contain only calibrated
                total power data);

CALDBE   (reorders the data array to contain only calibrated
                calibration values);

ZERO   (calculates the calibrated rms of the "zero" values
                and stores the rms in the CONDAR array VRMS(1));

AVGD   (computes the mean temperature and standard
                error of the mean of an ON/OFF sequence).

The verbs SWITCHED, TOTALPWR, CALDBE, and ZERO call the verb FIXDBE
implicitly, i.e., do not use FIXDBE before using these other verbs.
In general, observers will not need to use these verbs explicitly
as resident POPS procedures (see below) are available for standard
displays of switched and total power data.

The way in which FIXDBE calibrates depends on the value of the
control system flag "NT" as described above. If NT=1, indicating
the presence of a calibration signal phase, the data are scaled by
the factor

$$F_{CAL} = (TC/C) * \exp(A * ATTN) ,$$ (11)

where C is the average calibration signal from each sample, A is
the airmass and ATTN the zenith optical depth. If NT=0, indicating
no calibration signal, the data are scaled by the factor

$$F_{NO\_CAL} = (TC/DSF) * \exp(A * ATTN) ,$$ (12)

where DSF was described above.

The basic CONDAR data reduction commands are as follows:

scan#	S	(displays a switched power ON/OFF sequence);
scan#	T	(displays total power sequence);
scan#	CAL	(displays the calibration signals);
scan#	Z	(displays the zero signals);
scan#	M	(displays a mapping row).
scan#	F	(displays a five-point map.);
scan#	SPTIP	(displays vane-switched tipping scan.);
scan#	FOCALIZE	(displays a focus-check scan).
scan#	C1, C2, CB	(stacks scans with specified weighting -- see below.);

The procedure T, which displays a total power sequence, presumes that source emission is present in only one of the beam positions.

When NT = 1 (noise tube present), the verbs SWITCHED and TOTALPWR compute a system temperature and store the result in the header under the label TSYS. The computation of TSYS is by way of the equation

$$TSYS = \frac{\Phi_4}{\Phi_2 - \Phi_4} \quad TC = \frac{REF}{(REF + CAL) - REF} \quad TC \qquad (13)$$

A signal-to-noise figure of merit called TPSN is calculated and stored in the adverb VRMS(2). TPSN is the switched power signal divided by the total power signal and is given by
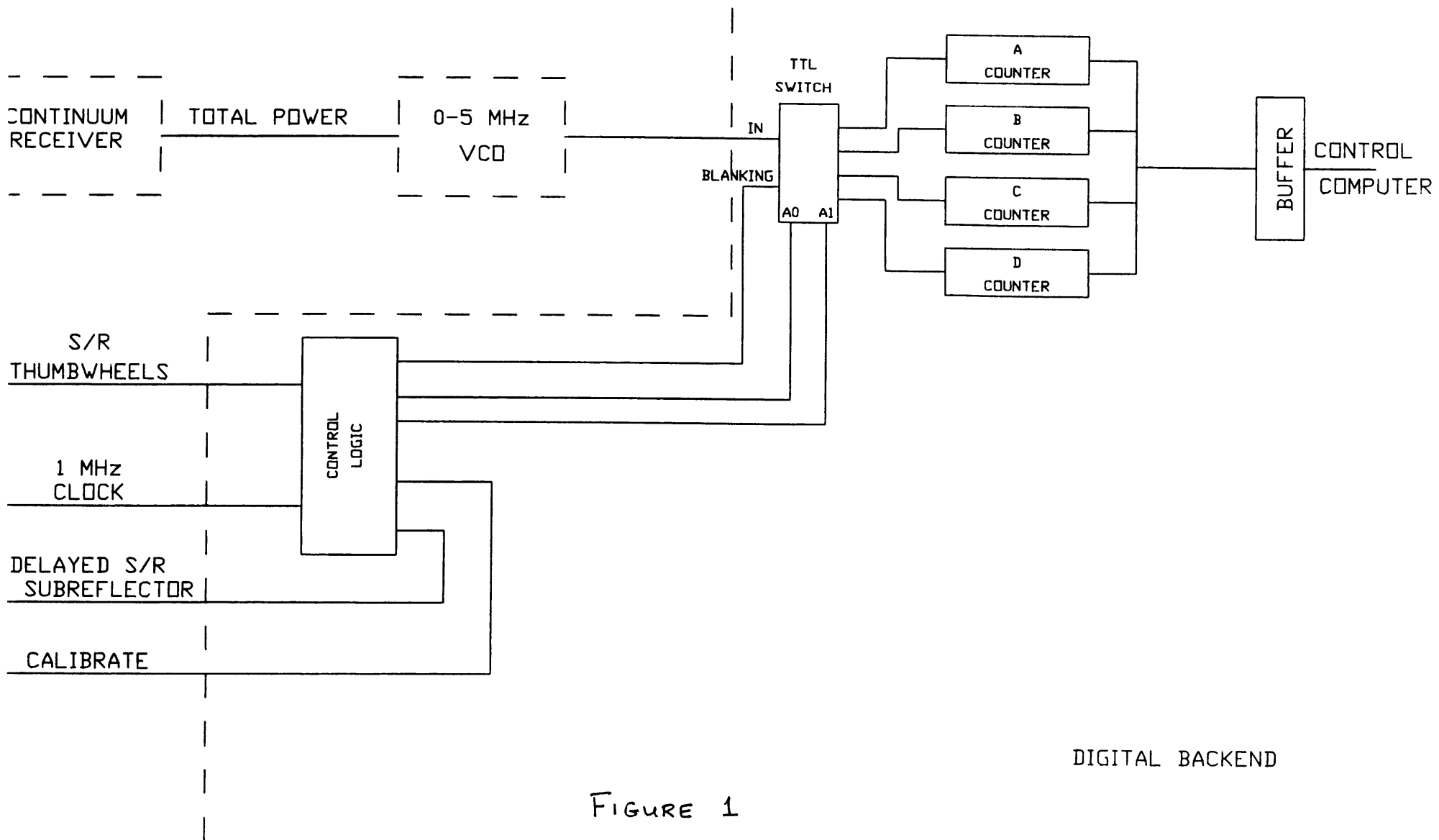
$$TPSN = \frac{\Phi_1 - \Phi_2 + \Phi_3 - \Phi_4}{\Phi_3 + \Phi_4} \quad (0.5) = \frac{SIG - REF}{SIG + REF} \qquad (14)$$

B. NOD2

The NOD2 data reduction program MAKMAP now contains a pre-processor for converting raw DBE data into calibrated switched or total power mapping points. When executing MAKMAP, you will be asked if the mapping data were taken in switched power or total power mode, i.e., with the subreflector nutating or fixed. All other NOD2 programs work the same as with SBE data.
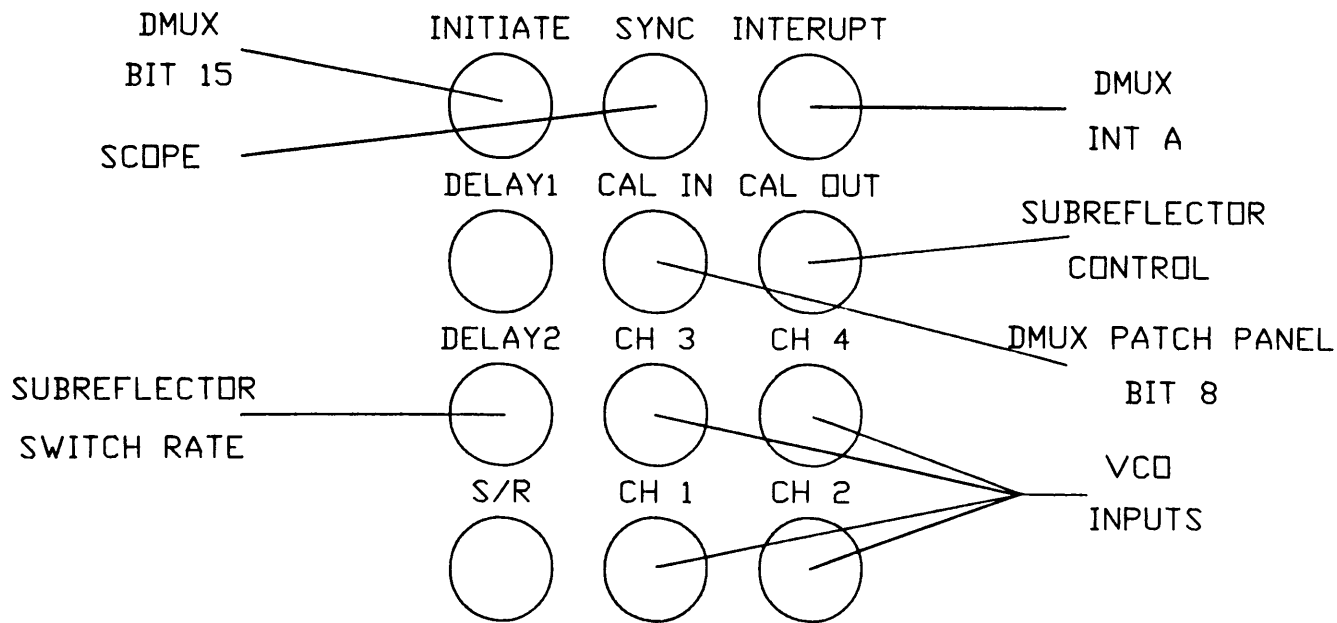
ACKNOWLEDGEMENTS

FIGURE 1

DMUX
BIT 15

SCOPE

INITIATE   SYNC   INTERUPT

DMUX
INT A

DELAY1   CAL IN   CAL OUT

SUBREFLECTOR

CONTROL

DELAY2   CH 3   CH 4

DMUX PATCH PANEL

BIT 8

SUBREFLECTOR

SWITCH RATE

S/R   CH 1   CH 2

VCO

INPUTS

DIGITAL BACKEND

FIGURE 2