RF TO OPTICAL FIBER: SWITCHING AND TRANSFER FUNCTIONS
A PROPOSAL FOR SOFTWARE

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## 1. INTRODUCTION

The GBT will have 50 Gregorian-focus receivers, some with more than one feed. (Why so many? Two for each feed [they are dualpolarized], and the upper frequency bands have two feeds per frequency.) and 8 prime-focus receivers (of which only two [dual polarization at a single frequency] will normally be operative simultaneously).

There will be 8 optical fibers to carry i.f. signals from the focal cage to the control room and back-end electronics. Of the 58 receivers, we must select 8 or fewer for the fibers. This selection must be specified by a set of switching parameters available to the user interface. These parameters should be user and software friendly and compatible with the broad specifications for the interface given in GBT Memo 81.

This is a large set of electronics and there is a correspondingly large number of possibilities for failure. The operational status of each receiver should be easily verifiable, both manually and automatically. One aspect of this verification should involve a comparison of measured and expected signal levels at various $t$ points. This test requires that each element in the signal chain be acterized in the software by a frequency-dependent transfer function so-that the signal level at any point in the chain can be predicted. These transfer functions should be user and software friendly and easily available for inspection by the user.

The present memo proposes a specific scheme for the switching parameters and extends the scheme to the transfer functions.
2. SWITCHING PARAMETERS.

All 58 receivers operate simultaneously and a user should be able to use any combinations of sets of receivers whether or not they are compatible with preplanned cabling arrangements, which might be based on 'conventional' astronomical requirements. For example, one could use Rx4 (3.95 to 5.85 GHz , turret position 4) together with Rxlo (18.0 to 22.0 GHz , turret position number 7)--which are on nearly opposite ends of a diameter of the turntable--simultaneously, even though one of the beams would be quite far off axis (this possibility is allowed with the currently-planned cabling). Or one could use Rxio (18.0 to 22.0 GHz ) together with Rxl4 ( 40 to 52 GHz ) simultaneously (this possibility is NOT allowed with the currently-planned cabling). The selection of which receivers provide signals to the control room is made with the Receiver Room IF Router and, if necessary and presumably only are cases, by changing cables by hand. Even if the flexibility in ver selection seems to limited by the local oscillator system, this apparent constraint can be overcome, at least temporarily, by handwiring in additional local oscillators.
transfer switches. Figure 1 depicts a preliminary version of the block diagram for the Router. Each SP8T switch selects among eight inputs and produces a single output. The eight SP8T switches are arranged in four strategically-chosen pairs, with the 16 inputs to each pair coming from 8 common feeds and orthogonal polarizations. Each transfer switch can interchange the signals of a pair. The 8 outputs from the four transfer switches go to the 8 optical fibers. For each SP8T switch, the 8 possible inputs are normally hard-wired according to prearranged plan so that predetermined combinations of receivers can be used simultaneously. However, if a user wants to use, simultaneously, a set of receivers that is impossible according this prearranged arrangement, the cabling can be changed by hand to accommodate.

There is a grand total (prime focus and Gregorian) of 58 receivers (which, herein, we designate R1 through R58) to be selected for 8 optical fibers (designated Fl through F8). With a standard cabling arrangement, each receiver corresponds to a particular input to the SP8T switches, but we want the ability to provide for nonstandard cabling arrangements. With 8 SP8T switches there are 64 i.f. lines (designated Il through I64). A straightforward way to specify these connections is with a 58 by 64 matrix $C$ (for CABLES), in which the 58 rows represent the receivers and the 64 columns the i.f. lines. This is a very sparse matrix, with only 58 nonzero entries; each nonzero entry is unity and 'connects' the r.f. to the i.f. line.

The standard cabling arrangement might (but probably will not) have receiver 1 (here designated Rl) connected to i.f. line I (II) (RlIl), R2 to I2 (R2-I2), (R3-I3), (R4-I4), (R5-I5), (R6-I6), (R7-I7); R8I9, R9-Il0, ...etc. In words: with 58 ( 7 times 8) receivers and 64 ( 8 times 8) i.f. lines, each block of 8 i.f. lines is connected sequentially to 7 receivers with the eighth i.f. line left unconnected. The matrix for this cabling arrangement is a straightforward modification of the unit matrix:


Suppose a user wished to interchange the cables for R3 and RI in both polarizations, as shown in Figure 2a, for testing or whatever purpose. The corresponding matrix is shown in Figure 2b, and is:

| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | etc. $\ldots(64$ columns $)$ |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |  |


| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

etc... (58 rows)
If we represent the receivers in $a \operatorname{l}$ by 58 matrix $R$ (for
RECEIVERS ) :

$$
R=\begin{array}{lllllllllll}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & \text { etc... }(58 \text { columns })
\end{array}
$$

then the matrix product $I=R C$ (I for I.F.) provides the receiver number at each of the 64 inputs to the I.F. Router. In the second example for $C$ above, we obtain
$I=R C=\begin{array}{lllllllllllll}3 & 2 & 1 & 4 & 5 & 6 & 7 & 0 & 10 & 9 & 8 & \text { ll etc..(64 columns) }\end{array}$
I is a l by 64 matrix.
These 64 i.f. signals are reduced to 8 outputs by the 8 SP8T switches. These switches are represented by $S$ (for SWITCHES), a 64 by 8 matrix. Each of the 8 columns of this matrix represents a different switch. Let each switch be designated by a 64 by l matrix Sn , with n running 1 through 8. Each matrix $S n$ has 8 possible values, corresponding to the 8 switch positions. In each Sn , each of the 64 elements is zero unless the switch connects to that particular i.f. input. For example, switch number 1 might be able to connect to i.f. lines l, 2, 3, ... in its eight positions. In this case, in position $l$ the matrix Sl is:

| 1 |  |
| :---: | :---: |
| 0 |  |
| 0 |  |
| 0 |  |
| 0 |  |
| Sl $=0$ |  |
| 0 |  |
| 0 |  |
| 0 |  |
| 0 |  |
| 0 |  |
| etc. | .. (64 rows) |

and in position 2,


The full SP8T switching matrix is the 64 by 8 matrix

The 8 outputs of these switches are represented by the matrix product $O$ (for OUTPUT); $O=I S=$ RCS. $O$ is a 1 by 8 matrix. Each successive pair of this matrix can be acted on by a transfer switch, of which there are four. The matrix of the transfer switches, $T$ (for TRANSFER), looks like

| T 1 | 0 | 0 | 0 |
| ---: | ---: | ---: | ---: |
| 0 | T 2 | 0 | 0 |
| 0 | 0 | T 3 | 0 |
| 0 | 0 | 0 | T 4 |

where each $\operatorname{Tn}$ is a 2 by 2 matrix and is equal either to

| 1 | 0 |
| :--- | :--- |
| 0 | 1 |

or
$0 \quad 1$
$1 \quad 0$
In Figure 2a, we assume the latter for Tl .
Thus, the receiver numbers that are connected to the 8 optical fibers are given by the matrix $F$ (for FIBERS), a l by 8 matrix; $F=O T$ $=$ RCST. For the switch settings assumed in Figure 2a, the optical fibers F1 and F2 are connected to receivers R1l and R2.

## 3. TRANSFER FUNCTIONS.

All 58 receivers operate simultaneously and one should be able to verify that any one is working properly whether or not it is in use. For example, a careful observer may wish to verify that the systems she intends to use work correctly, well before beginning her observing while another observer is using a different set of receivers. This verification requires comparing measured and expected signal levels and injecting known signals at various points to see the results later in the receiver chain. If each component in the chain is represented by a transfer function, which is in general a complex gain as a function of frequency, and if the receiver, cal, and antenna temperatures are known, then calculating the expected signal level is straightforward.

The matrix representation discussed above lends itself naturally to this characterization. There is one addition, however: the 'receiver' is, itself, a chain of devices. Each device has its own transfer function and is subject to failure, so that signal injection points and test points exist within the receiver itself. Thus, the number of transfer functions is inevitably larger than the number of switching parameters. Figure 3 depicts the block diagram of a generic receiver, together with representative values of realistic transfer functions at a single frequency, and illustrates what is required. Note that in Figure 3, which is for the purposes of illustration, we eliminate complexity by writing only the real and not the imaginary (phase) portions of the complex gains, and we do not include their frequency dependencies.

1 by 1 matrix and does not need the complexity of matrices. But this is nat the case for at least two types of device: the front-end polarizer and the transfer switches within receivers, which are used to interchange the two polarizations.

The polarizer generates RCP and LCP from the linear polarizations derived from the feed. We use a 2 by 2 matrix specify this polarization conversion. If the conversion were perfect, this would be a unit matrix: pure linear in, pure circular out. However, the devices cannot be perfect, so there is a small admixture of LCP in the RCP channel and vice-versa. In Figure 3, we have assumed a lossless polarizer and cross-polarization of $1 \%$ and $2 \%$ for the two outputs. This cross polarization (which is a function of frequency) is rather easily calibrated in the lab and should remain constant with time because the polarizer is a mechanical device.

The transfer switches interchange the two polarizations after amplification and may have both loss and crosstalk. In Figure 3, we have assumed loss of a few percent, depending on the switch position, and zero crosstalk. Again, these characteristics are easily calibrated in the lab and should be stable.

Transfer functions depend on frequency. This frequency dependence must reside in the software. The frequency dependence needn't be characterized precisely. Rather, an approximation to the shape of the sort one sees on a conventional spectrum analyzer is sufficient. There are three areas where this frequency dependence is particularly important. One area includes the r.f. feed gain, the r.f. amplifier gain, and the receiver temperature; knowing these allows the user to rmine, among other things, how far the user can push a system de of its nominal frequency range. Another area is the shapes of and i.f. filters. The third area is the mixing process, where the upper and lower sidebands can become irretrievably combined if the local oscillator frequency is so selected.

A user should be able to display a graph of the overall system gain and signal level as a function of frequency at virtually any point in the receiver chain so that the user can verify system performance and make a knowledgeable selection of local oscillator frequency.

The generic receiver of Figure 3 is set up for circular polarization, so we specify the antenna temperature for the two circular polarizations in a 1 by 2 matrix TA (for ANTENNA TEMPERATURE). These are then acted on by the feed/polarizer combination, which operates on them with a 2 by 2 matrix POL (for POLARIZER); this is nearly a unit matrix, with the departures from unity indicating the cross polarization. The calibration signal from the noise diode can be added to the antenna temperature in a 1 by 2 matrix TCAL--if the cal is 'turned on' with its switch SCAL (for CALIBRATION SWITCH). The receiver noise (TR, for RECEIVER TEMPERATURE) is added to this combination and the resulting signal is amplified by the cooled r.f. amplifier GRFl (R.F. GAIN NUMBER 1). This goes to the transfer switch, represented by the 2 by 2 matrix ST (for TRANSFER SWITCH). Then comes more r.f. amplification GRFl, a filter, a mixer, i.f. filter, and i.f. amplification...

The front end of this receiver chain, together with representative values for the matrices, are shown in Figure 3. The signal levels at the input to the mixers are given by the 1 by 2 matrix
$\{T A * P O L+[(S C A L * T C A L)+T R]\} * G R F 1 * S T * F R F * G R F 2$

The next stage in this chain is mixing with the first l.o. The mixing process has its own complex gain, which is a function of both r.f. and l.o. frequency and is describable by matrix multiplication as above. But its whole raison d'etre is the addition and/or subtraction of a constant (the l.o. frequency) to/from the frequency axis in the
frequency-dependent gain; in other words, the mixer may pass either both or only one sideband. We must define a new operator, the mixing operator, which we denote by the usual symbol used in block diagrams, W. With this operator,

$$
\text { I.F. }=\text { R.F. } \nmid \text { L.O. }
$$

In this equation, R.F. is the matrix of r.f. inputs to the mixers and is given by equation (1); and L.O. is the matrix of the l.o. frequencies to the mixers.

With this mixing operator, the extension of our matrix representation of the transfer functions and signal levels to the mixer and beyond to the back ends is straightforward and we do not bore the reader with its repetitious details here.

In summary, this system of representation allows one to predict the signal levels at any point, knowing only the antenna temperature at the position where the telescope happens to be pointed. One can inject a signal at any point and predict the effect at any other point. And a user can examine the frequency dependence of the transfer function of any component, or the signal level at any point in the receiver, by examining appropriate matrices or combinations of matrices.

## 4. COMMENTS ON THE USER INTERFACE.

In the monitor and control system, we need an interface to the user (the 'user' can be the engineer, technician, telescope operator, astronomer) that performs many functions. The functions relevant to the present memo include:
l. Allows the user to specify the observing configuration-which set of receivers and feeds is to be used with which back ends.
2. Allows the M\&C system to easily tell both itself and the user what is connected to what.
3. Allows the user to specify the parameters of each system, for example the central frequency.
4. Allows the user to determine whether each system is functioning properly.

The broad specifications for the interface were specified in GBT Memo 8l. We extract a highly abbreviated list of interest here:

1. Each significant hardware device should have a 'control panel' interface to the user. This is also called a 'graphical user interface', or GUI. One should be able to specify system parameters and keywords on the GUI with a mouse and/or the keyboard. The entire set of keywords and parameters can be stored and recalled as ASCII files, which can be edited with standard text editors.
2. One should also be able to specify each parameter and keyword at the command line level, either from the keyboard or by reading or executing command files.

The matrix scheme outlined above should be commensurate with these requirements. At its simplest, it rather easily allows commandline interaction because each element of a matrix, or the state of a switching matrix, can be represented by a numerical value and the notation involved is familiar and straightforward.

More important for initial setup and system evaluation is the GUI. The matrix representation works naturally with the ideal GUI for electronic systems, which is a block diagram. For example, a block diagram of the whole system, including the cabling arrangement, can be displayed together with the matrix of cable and switching connections; the matrix representation, in which rows are inputs and columns are outputs, is easy to comprehend. A user, armed with a mouse, should be able to click on one part of this block diagram and, for example, change the status of a switch; this changes the resulting matrix and the block diagram should reflect this change clearly. The user should be able click on a test point and view the expected frequency dependence of the signal level. And a user should be able to expand the block diagram to look at one portion of the system, for example the receiver, in more detail.

## FIGURE CAPTIONS

Figure 1. A preliminary version of the block diagram for the I.F. Router.

Figure 2a. Simplified block diagram of the overall GBT receiver-to-optical-fiber system. There are 58 receivers, represented by Rn along the top row. C is the cable network that connects the receivers to the 64 i.f. lines In. $S n$ are the 8 i.f. Switches that select among the i.f. lines. Tn are the 4 transfer switches, each of which jnterchanges the members of a pair its inputs.

Figure 2b. Sample numerical values for the matrices that describe the interconnections shown in Figure la.

Figure 3. Simplified block diagram of a generic dual-polarized receiver, illustrating the signals and transfer functions required to predict the signal level at any point. For illustrative purposes, we include numerical values for only the real part of typical transfer functions for a single frequency. In reality, each transfer function should be a function of frequency and may include not only amplitude but phase.



$$
\pi \cdots \in 2
$$

$$
I=[3214567010981112 \cdots 58.0] \quad(64 \text { colvinns })
$$



$$
s_{2}=\left[\begin{array}{c}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
1 \\
\vdots \\
\vdots \\
\vdots
\end{array}\right.
$$

$$
\begin{aligned}
T_{1} & =\left[\begin{array}{ll}
0 & 1 \\
1 & 0
\end{array}\right] \\
F & =\left[\begin{array}{lll}
11 & 2 & \ldots
\end{array}\right]
\end{aligned}
$$



