The GBT Observer Interface: II. How an Observer Can Configure I.F. Hardware

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I. Introduction

This memo discusses the characteristics of a possible observer's interface to the I.F. hardware of the Green Bank Telescope (GBT). For several reasons we should consider afresh how an observer can specify the hardware that is to be placed between the chosen receivers and backends. First, observers will be able to use several receivers and backends simultaneously, a flexibility rarely found on older radio telescopes. Second, in the current design of the GBT, almost all of the hardware and switches that will exist between the receivers and backends are under computer control. Third, the monitor and control software is supposed to attach a complete description of the I.F. hardware to the data. Obviously, the user should be able to specify the I.F. hardware with a well-constructed, easy-to-use computer interface. We hope that the interface we sketch out will help in the design and construction of an interface that observers will use with the GBT.

II. Controlled Equipment

The I.F. equipment that the user interface will control consists of the sequence of oscillators, multipliers, power dividers, amplifiers, attenuators, and mixers that make up the path or chain between a chosen set of receivers and a set of backends. The I.F. chains for the GBT, or any radio telescope, have several characteristics that we considered when we designed our suggested user interface. For example:

- For each I.F. input on a backend there exists a path that begins at a receiver.
- Paths from a receiver can fork going to many I.F. inputs but, except for the cases we mention below, paths from two or more receivers cannot terminate at a single I.F. input (i.e., usually, paths can only fork from receivers to backends and not from backends to receivers).
- There will be as many I.F. chains in use as there are I.F. inputs in use.
- Some chains will require one or more mixers; some can require none
- The order of the mixers in a chain is important.

- All mixers must have an associated oscillator but more than one mixer can share the same oscillator.
- Some I.F. chains can share mixers.
- Some mixers can have an associated multiplier.
- Every oscillator can have one or more associated mixers.
- Between any oscillator and its associated mixers can be one or more multipliers.
- The order of multipliers between an oscillator and mixer is important.
- Two or more oscillators cannot share the same multiplier.
- Every multiplier must have an associated mixer and oscillator.
- If an oscillator feeds two or more mixers, some or all of the multipliers between the oscillator and each mixer can be different.
- Two or more mixers can share the same multipliers (and, if they do, they then must share the same oscillator).
- Each oscillator can have one or only a few discrete frequencies that they can generate (i.e., they can be considered fixed in frequency during an observation run).
- Some oscillators can be tuneable to a high degree of resolution.
- Some tuneable oscillators can be under computer control.
- Depending upon whether an observer wants to Doppler-track (i.e., correct the observing or sky frequency for the motion of the telescope with respect to some frame of reference), some oscillators can have their frequencies altered during or between observations.
- All aspects of Doppler tracking can be changed from one observation to the next or can differ between I.F. chains.

Figure 1 gives example I.F. chains, some simple and some complicated, that we think the user interface should be able to set up and describe.

We know of at least two exceptions to the above rule concerning how I.F. chains should only fork from receiver to backend but never from backend to receiver. The first arises when two I.F. chains from two receivers of identical sky frequency but of opposite circular (or linear) polarizations are combined in a hybrid to produce two outputs of linear (or circular) polarizations. The second occurs in beam switching when a rapid switch takes two input I.F. chains (from two receivers of identical sky frequency but different feeds) and produces a single, switched I.F. output. In both cases, the output of the hybrid or switch depends upon two receivers. Figure 2 gives examples of these common situations that the user interface should handle.

III. Guidelines for a Good User Interface

At its simplest, any user interface for the GBT should allow the observer to choose the number of I.F. chains and the receivers, mixers, multipliers, oscillators, and backends in each chain. The GBT will have some half dozen switches, called routers, which govern, for example, which oscillator feeds which multiplier or mixer, which I.F. feeds which backend, etc. For the most part, when an observer, through the user interface, makes a choice of equipment, the control software should alter the state of the routers to achieve the desired configuration. Since the routers are not infinitely flexible, some configurations might be impossible and the control software and user interface should warn the user of the impossibility.

The user interface should provide parameters to the control software beyond the desired layout of I.F. equipment. For example, the interface must specify which oscillators are fixed in frequency, what these fixed frequencies are, which oscillators are to be used for Doppler tracking, and which definition of Doppler tracking the user wants.

The interface should return to the user the complete status of the hardware. The data acquisition software should attach to the data a complete description of the I.F. system for documentation and data analysis purposes.

The user interface for controlling and monitoring the I.F. must allow for many possible combinations of devices and the parameters of the devices. We think that the number of combinations and possibilities, although large, can be specified within the GBT user interface in a few easy-to-learn and human-oriented ways. The user interface should be designed to cover not only what today will be possible with the planned GBT equipment but also what might be available over the lifetime of the user interface.

IV. Existing Models for Describing I.F. Chains

We know of four existing and different models, philosophies, or schemes that have been put forward for specifying and summarizing I.F. chains. At least two of the models are in use at NRAO telescopes and we suggest the reader look at the user manuals of the telescopes for further details.

(a) Matrix Operations

Carl Heiles, in GBT memo 106, describes how one can use the properties of matrices to represent the actions of the routers, mixers, and oscillators in I.F. chains. Although matrices might be an excellent way of describing what goes on between receiver and backend, they may or may not be an appropriate tool that an observer uses to specify their desired I.F. chain. For example, we think that they may be too cumbersome for a casual user of the telescope but they may be appropriate tools that programmers can use to manipulate or describe the hardware. Memo 106 does not describe an interface that observers could use to specify both the contents of the matrices and the operations performed between matrices. We suggest that readers familiarize themselves with memo 106 since we occasionally will make use of the ideas presented there.

(b) Specifying I.F. Equations

Some telescopes, like the 140-ft, use a mathematical equation to describe the I.F. chain. If only one oscillator is tuneable and is used for Doppler tracking, any chain can be described with the following equation that relates the sky frequency to the frequency of the tuneable oscillator (LO) and the frequency of the I.F. when it terminates at the input of some backend:

$$:y\,Frequency = \pm(LO \cdot \prod_j M_j) \pm IF + \sum_i (S_i \cdot F_i \cdot \prod_k m_i \qquad \textbf{(1)}$$

The M_j are the multiplication factors applied to LO, F_i the frequencies of the fixed oscillators in the chain, m_{ik} the multiplication factors applied to F_i, and S_i either +1 or -1, depending on whether F_i uses an up- or down-converting mixer. Table 1 gives the equations for the chains of Figures 1 and 2.

Each I.F. chain requires a separate equation and, as is obvious, much of the equipment setup remains hidden from the user. For example, which oscillator is LO and which are the F_i? What is the order of the mixers in the chain? What equipment is shared between I.F. chains? Where are the polarization hybrids?

Although equations are flawed in that they hide the hardware details from the user, equations quickly and conveniently summarize I.F. chains for the user. We find that summarizing I.F. chains with equations helps us understand what is going on but we realize that equations may not be the best way for novice users to set up I.F. chains. The careful reader of memo 106 will notice that the products of the described matrix operations will be a set of equations, one for each I.F. chain, that are mathematically equivalent to the above equation.

(c) Specifying I.F. parameters

Other telescope control systems, like that used at the 12-m and the 300-ft, have (or had) a user interface that assumes a fixed I.F. chain with parameters (multiplication factors, offset frequencies, etc.) the observer supplies by assigning values to variables in the user interface. For example, the observer supplies values for the multiplication factors of multipliers, the frequencies of the fixed oscillators, and flags telling whether a particular mixer is to use upper or lower sidebands.

We note a few obvious disadvantages. The user must know from other sources how the terms they enter are used so that they can recreate and apply equation (1). The interface might set limits to the flexibility of the I.F. chain more then the hardware sets limits. As an advantage, the users are intimately aware of how each piece of equipment is set up. Novice users of the telescope, when they are supplied with a set of suggested values, never need to concern themselves with the details of the I.F. chain. In many ways, the flaws and advantages of this scheme are exactly opposite those of section IV.b. With this type of user interface, the observer is supplying values for some cells of the matrices discussed in memo 106 but the control software has predetermined the type and order of operations performed between the matrices.

(d) Graphical User Interface

Alternatively, a graphical user-interface (GUI) might use symbols to describe pictorially, like a flow chart, the I.F. cables, oscillators, multipliers, mixers, switches, or routers for each I.F. chain (Figures 1 and 2 are examples of what a GUI display might look like). In a good GUI, the user can modify on the computer screen using a mouse the equipment setup by rearranging symbols that represent the various hardware components. A good GUI should allow the user to alter and understand, as easily as the method of section IV.c, the hardware parameters (e.g., oscillator frequencies or multiplier settings).

With a well-designed GUI, the observer can understand quickly the sequence and settings of equipment in each I.F. chain. However, some people hate GUI interfaces and others cannot use them because of hardware limitations or physical disabilities. GUI's usually give a false sense of flexibility since they present what look like many possible configurations but, in reality, only a few can be handled by the hardware. The computer screen might become confusing if one had many I.F. chains. A GUI might become cumbersome or useless for 'batch' observing when an observer can schedule beforehand a desired change to part of the I.F. chain but won't be around to rearrange the symbols on the screen at the appropriate time. GUI's may not intrinsically summarize each I.F. chain in the form of the easily-understood equation (1). Thus, although we believe a GUI should be part of the user interface, we require that another type of user interface must be available. Note that software should be able to take the contents of the matrices of memo 106 to generate GUI's displays (and vice-versa).

V. An Easy-to-use Table Model for Describing I.F. Chains

Each of the discussed models for specifying I.F. chains have their advantages and disadvantages. Here, we present an additional scheme for specifying I.F. chains that uses tables and that, in philosophy, lies somewhere between the matrices of memo 106 and the systems used at other telescopes. Our table scheme has as many flaws and advantages, though different ones, then the other models. We will discuss tables in detail not because they are better or more important than other methods but because we know of no other place where this method has been discussed. We propose that the GBT user interface should provide all of the methods.

In our scheme, each I.F. chain is described by a table. The fields or cells of the table describe the components of the I.F. chain. Rows in a table represent the actions performed on the I.F. by the combination of a mixer and its associated multipliers and oscillators. The number of rows is the number of mixers in an I.F. chain and the order of the rows represents the order of mixers in the I.F. chain.

The columns of the matrices could describe for each mixer:

- the designation or name of the mixer.
- the designation of the oscillator that is to be used with that mixer.
- the designation of the multipliers (if any) that is associated with the oscillator and the multipliers' multiplication factor (which would be a value of one if no multiplier is associated with the oscillator and mixer).
- the order of multipliers in the columns of the table represents the order of multipliers between oscillator and mixer.
- whether the mixer is an up- or down-converter and, if a down converter, whether it is an upper, lower, or double sideband mixer.

If the designation for a mixer, oscillator, or multiplier in one table is the same as that in another table, then the two I.F. chains have the mixer, oscillator, or multiplier in common. The control software can easily figure out what are to be the state of the routers by looking at what tables use what mixers and what mixers use what multiplier and oscillator. Tables 2-15 represent the I.F. chains depicted in Figures 1 and 2.

In addition to the columns already described, a separate column of the table could describe how the frequency of the oscillator is set. For example, if an oscillator must have a fixed frequency, the column might state that the oscillator's frequency is fixed and contain the value of that frequency. If the oscillator is the one whose change in frequency performs the user's desired Doppler tracking, then the column might indicate that the oscillator is under computer control and the interface would insert into the table the frequency set by the computer. If two or more I.F. chains share an oscillator, then the column in the tables for the other chains should indicate that the oscillator has its frequency determined by the first I.F. chain and the interface should insert the frequency into the table.

A final column in the table might describe for those oscillators under computer control how the computer is to set the frequency. For example, in some work, the user might not want to Doppler-track in which case they should supply: the form of the Doppler equation, the rest frame they want to use, parameters indicating how often the computer should update the oscillator's frequency, and the velocity that they want at the center of the I.F. bandwidth. We will describe further in section VI the parameters a user should supply to obtain their desired method of Doppler tracking.

The user must specify for each table the name of the receiver, the rest frequency at the center of the I.F. bandwidth, and any other receiver information. He or she must also supply the name of the backend, the I.F. input, the center frequency of the I.F., the bandwidth of the spectrometer, and any other backend information (see Fig. 1 and Tables 2-8).

If an I.F. chain contains a polarization hybrid or I.F. switch (for beam switching), the chains must be broken into two sets of tables. The first set describes the chains between the receivers and hybrid (or switch), and the second describes the chains between the hybrid (or switch) and the inputs of the backends (see Fig. 2 and Tables 9-15).

The user interface must protect the user from specifying illegitimate or contradictory information. It should help the user by filling in as much of the table as is reasonable. Since chains may share equipment, as the user changes fields in one table the interface should alter all the relevant cells in the other related tables. Some values in the cells of the table may be dictated by the hardware, and shouldn't be altered by the user, so the interface must lock them from being modified. Other cells have their contents determined by the values in related tables and the interface should lock these cells from being modified. We think the interface should make it obvious to the user which cells it has locked and should provide the user some help in finding out the relationships between cells of tables.

Some rules that tables must follow are:

- Two or more tables can have the same common oscillator but only one table can use that oscillator for Doppler tracking; all other tables

must specify that another table has determined the oscillator's frequency.
- In any table, only one oscillator can be used for Doppler tracking. The frequency of all others must be either fixed or determined by another table.

We recommend that the programmers for the GBT create a user interface that will manipulate these tables and that should be similar to a spread sheet program. The interface, for example, might create the proper number of tables once it knows how many backends and I.F. inputs (i.e., I.F. chains) the observer will use. Once the user specifies the backends, receivers and a rest frequency, the interface might fill in as many cells in the tables as it can. The interface might display the tables and the observer, using mouse and keyboard, can modify the values in the tables' cells. As the observer alters cells in one table that have hardware in common with one or more other tables, the interface must properly update the cells in the other chain's table (and warn the user of the changes made). The user should be able to store and retrieve tables from disk (using their own file names). In addition to a spreadsheet program, the programmers for the GBT should provide, for batch-like observing, a command-line interpreter that an observer can use to retrieve and store tables, and query and change the value of any cell in any table.

Tables can be easily converted into the matrices of memo 106 or can serve as input to or output from a flowchart GUI. They can be reduced into the equivalent of equation (1); from the cells within the table, the user can easily read the parameters for each piece of hardware as in the method described in section IV.c. We think the interface should convert between the various methods of representing I.F. chains since the methods have flaws and advantages that complement each other. Each observer can then use and switch between whatever method they want to use to set up and display their I.F. chains.

We see as an advantage of tables how easy they can be converted to any of the methods described in IV (i.e., the table method is almost a super-set of the other methods). Note that converting from methods IV.b and c to tables will usually be impossible due to limitations of these less-sophisticated methods. The table method is highly flexible and allows in a straight forward way for all the future hardware changes we can envision. Tables hide the status of the routers from the user (which might be a welcome simplification for most observers but a possible disadvantage to staff trying to debug problems). With many I.F. chains, tables probably will be no more cumbersome than the other methods.

VI. Specifying How to Perform Doppler Tracking

To Doppler-track, the observer must specify their desired form of the Doppler equation (e.g., radio, optical, or relativistic definitions), the frame of rest (e.g., LSR, heliocentric, topocentric, geocentric, etc.), and the velocity they would like centered in the I.F. bandpass in that frame of rest. The user interface should also accept a user-defined frame of rest, in which case the observer would specify a velocity of motion and the frame in which this velocity is based, an apex coordinate (X and Y), and the coordinate system of the apex (e.g., Galactic, R.A./Dec., Ecliptic) (see Table 6).

At least one oscillator in an I.F. chain must be under computer control and have sufficient frequency resolution to Doppler-track. The rate at which the control software updates the oscillator's frequency usually depends upon the channel width of the spectrometer--the narrower the channel, the more frequent the need to update. The user interface, for example, could accept either an update rate or a frequency tolerance (which the program can use to calculate the update rate). Since the update rate should be some multiple of the backend's dump time, the dump time might be determined from the update rate (or vice versa).

Each chain might have its own high-resolution, tuneable oscillator that does the Doppler tracking (i.e., the oscillator is not shared with other I.F. chains). In this simple case, the oscillators in each chain might be updated at different rates because the backend channel widths might differ. If the sky frequencies of the I.F. chains differ then each chain's oscillator might be adjusted by different amounts since the formulae that describe Doppler tracking depend upon sky frequency. The first I.F. chain in Figure 1 (and Table 2) describes this type of I.F. chain.

If multiple I.F. chains share the same tuneable oscillator, then the way Doppler tracking is handled (e.g., the form of the Doppler equation, the frame of rest, and the update rate) can only be specified for one I.F. chain and all other chains will have their Doppler tracking determined for them. An example would be the fifth and sixth I.F. chains in Figure 1 (and Tables 6 and 7). If the rest frequencies differ between the I.F. chains, then the Doppler tracking will only be correct for one chain. There is no way to correct the data for these incorrect I.F. chains while data are being taken but the data might be corrected afterwards. For example, if the backends dump the data at a rate equal to or better than the rate at which the problematic chains should have their frequencies updated, then the data analysis software can shift the data from each dump by appropriate amounts before averaging the dumps.

Multiple I.F. chains at different sky frequencies that share a high-resolution, tuneable oscillators might have a second tuneable oscillator. Here, the second oscillator in each chain can be used to correctly keep the I.F. chain properly Doppler tracking. That is, the errors introduced by the shared oscillator could be corrected by updating the frequency of the second oscillator. The second and fourth I.F. chains in Figure 1 (Tables 3 and 5) are an example.

The user interface must allow for using the Doppler correction at a position and time other than the current. This will be useful when an observer is making position-switched, spectral-line observations. The observer would like the sky frequencies of their on-position observations to be identical to those of their off-position observations. The user must then specify, for example, that their off-position observation should use, for all Doppler calculations, the position and time the telescope was or will be performing the on-position observation. Thus, the on- and off-position observations will be taken at the same sky frequencies, which will result in better subtraction of the off-position data from the on-position data.

VII. Conclusions

We believe that a very flexible and complete user interface must be built to handle the sophistication and uniqueness of the I.F. hardware of the GBT. Since we find no one method of setting up or describing I.F. chains adequate, we suggest that the user interface be based on a combination of the four methods described in section IV, some of which are in use at existing telescopes, plus the method we put forward in section V. The user interface should satisfy all of the criteria we list in section III and must handle the types of Doppler tracking we describe in section VI.

Table 1: I.F. equations for the chains in Figures 1 and 2.

Figure	Chain	Sky Frequency
1	1	a.3 - 250.0
1	2	a.6*4*2 + a.7 + 100
1	3	a.6*4*2 + a.7 + a.8*2 - 300
1	4	a.6*4 + a.7*2*6 - a.9 + 300
1	5	a.9 - 133
1	6	a.9 - 135
1	7	...
2	1	a.14 + a.15a + 300
2	2	a.14 + a.15b + 300
2	3	a.16a + a.16b*2 + a.16c*2 + 500

Table 2: Describes the first I.F. chain of Fig. 1.

Receiver information: Receiver = A Rest Frequency = 1667.012345						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
3a	a.3	none	1x	Lower	Computer [F=1817.01]	Def: Radio Frame: LSR Vcenter=0.0 df=0.01
Backend information: Backend:5 Input:12 Freq=-250 Bandwidth=160						

Table 3: Describes the second I.F. chain of Fig. 1.

Receiver information: Receiver = B Rest Frequency = 1420.4058						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
12b	a.6	m14 m11	4x 2x	Upper	Fixed F=125.00	...
12c	a.7	none	1x	Upper	Computer [F=320.00]	Def: Radio Frame: SUN Vcenter=100 df=0.001
Backend information: Backend:2 Input:3 Freq=100 Bandwidth=40						

Table 4: Describes the third I.F. chain of Fig. 1.

Receiver information: Receiver = B Rest Frequency = 1420.4058						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
12b	a.6	m14 m11	4x 2x	Upper	Determined [F=125.00]	...
12c	a.7	none	1x	Upper	Determined [F=320.00]	...
12d	a.8	m12.d	2x	Lower	Computer [F=200.00]	Def:Optical Frame: None Vcenter=-12.234 df=1.e-4
Backend information: Backend:2 Input:4 Freq=-300 Bandwidth=0.125						

Table 5: Describes the fourth I.F. chain of Fig. 1.

Receiver information: Receiver = C Rest Frequency = 2840.8106						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
12e	a.6	m14	4x	Upper	Determined [F=125.00]	...
12f	a.7	m32 m33	2x 6x	Lower	Determined [F=320.00]	...
12g	a.9	none	1x	Lower	Determined [F=1800.0]	...
Backend information: Backend:1 Input:1 Freq=300 Bandwidth=15						

Table 6: Describes the fifth I.F. chain of Fig. 1.

Receiver information: Receiver = D Rest Frequency = 1667.012345						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
12g	a.9	none	1x	Lower	Computer [F=1800]	Def:Radio Frame:User df=.1 Vcenter=0 RADEC 1950 wrt:LSR X=17h12m13.3s Y=-12d14m11.1s V=-345.23
Backend information: Backend:1 Input = 2 Freq=-133 Bandwidth=15						

Table 7: Describes the sixth I.F. chain of Fig. 1.

Receiver information: Receiver = D Rest Frequency = 1665.012345						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
12g	a.9	none	1x	Upper	Determined [F=1800.0]	...
Backend information: Backend:1 Input:3 Freq=-135 Bandwidth=40						

Table 8: Describes the seventh I.F. chain of Fig. 1.

Receiver information: Receiver = E Rest Frequency = 220.123456						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
none	...	...	...	...	...	...
Backend information: Backend:5 Input:1 Freq=220.123456 Bandwidth=0.078						

Table 9: Describes the I.F. chain between first receiver and hybrid of Fig. 2.

Receiver information: Receiver = F Rest Frequency = 1850						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
14a	a.14	none	1x	Upper	Fixed F=1250.0	...
Hybrid information: Hybrid: 1 Input: 1						

Table 10: Describes the I.F. chain between second receiver and hybrid of Fig. 2.

Receiver information: Receiver = G Rest Frequency = 1850						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
14b	a.14	none	1x	Upper	Determined [F=1250.0]	...
Hybrid information: Hybrid: 1 Input: 2						

Table 11: Describes the first I.F. chain between hybrid and first I.F. input of Fig. 2.

Hybrid information: Hybrid: 1 Output: 1						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
15a	a.15a	none	1x	Upper	Fixed F=300	...
Backend information: Backend:2 Input:1 Freq=300 Bandwidth=40						

Table 12: Describes the second I.F. chain between hybrid and second I.F. input of Fig. 2.

Hybrid information: Hybrid: 1 Output: 2						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
15b	a.15b	none	1x	Upper	Fixed F=300	...
Backend information: Backend:2 Input:2 Freq=300 Bandwidth=40						

Table 13: Describes the I.F. chain between third receiver and I.F. switch of Fig. 2.

Receiver information: Receiver = H Rest Frequency = 10000						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
16a	a.16a	none	1x	Upper	Fixed F=5000.0	...
16b	a.16b	m16	2x	Upper	Fixed F=2000.0	...
Switch information: Switch: 1 Input: 1						

Table 14: Describes the I.F. chain between fourth receiver and I.F. switch of Fig. 2.

Receiver information: Receiver = I Rest Frequency = 10000						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
17a	a.16a	none	1x	Upper	Determined [F=5000.0]	...
17b	a.16b	m16	2x	Upper	Determined [F=2000.0]	...
Switch information: Switch: 1 Input: 2						

Table 15: Describes the third I.F. chain between switch and third I.F. input of Fig. 2.

Switch information: Switch: 1						
Mixer	Oscillator	Multiplier	Fact	Sideband	Control	Doppler
16c	a.16c	m16b	2x	Upper	Fixed F=250	...
Backend information: Backend:3 Input:1 Freq=500 Bandwidth=300						

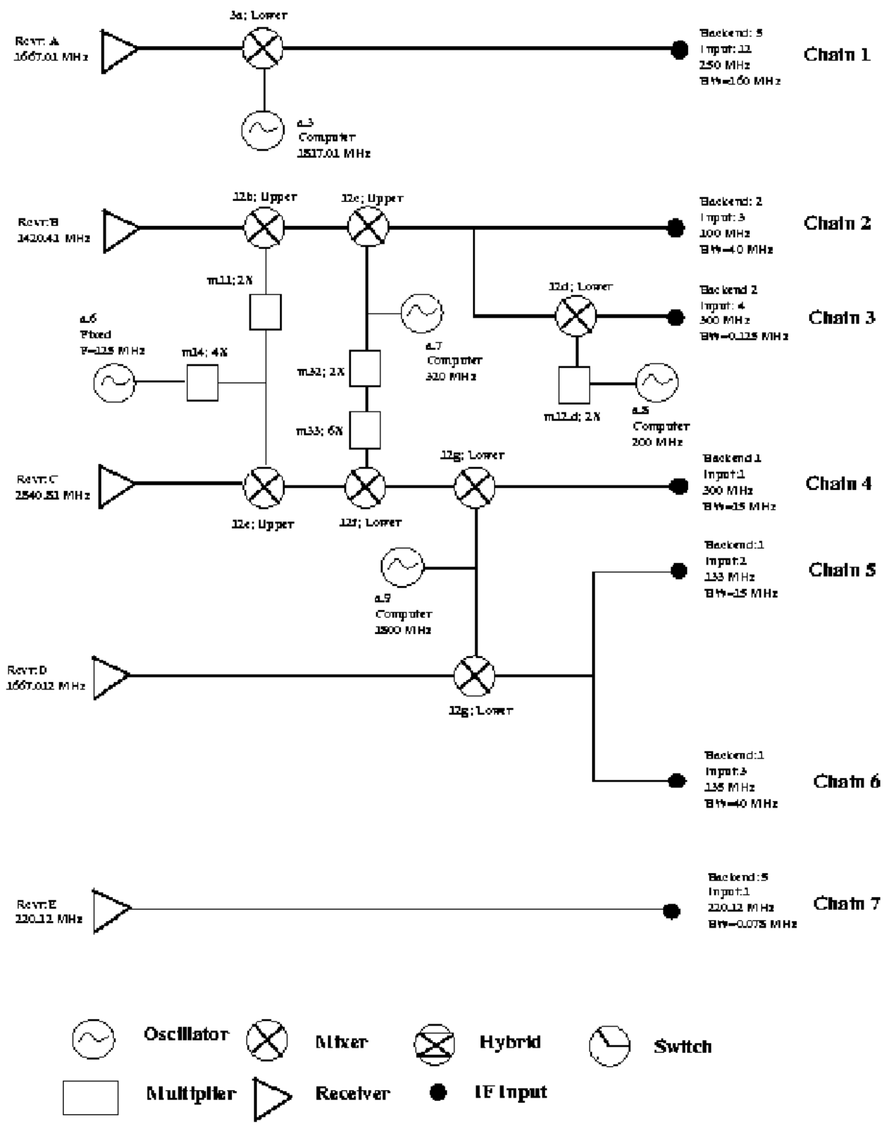

Figure 1: Seven I.F. Chains, which use five receivers, with no I.F. chain originating from more than one receiver. We have chosen completely arbitrary names for devices.

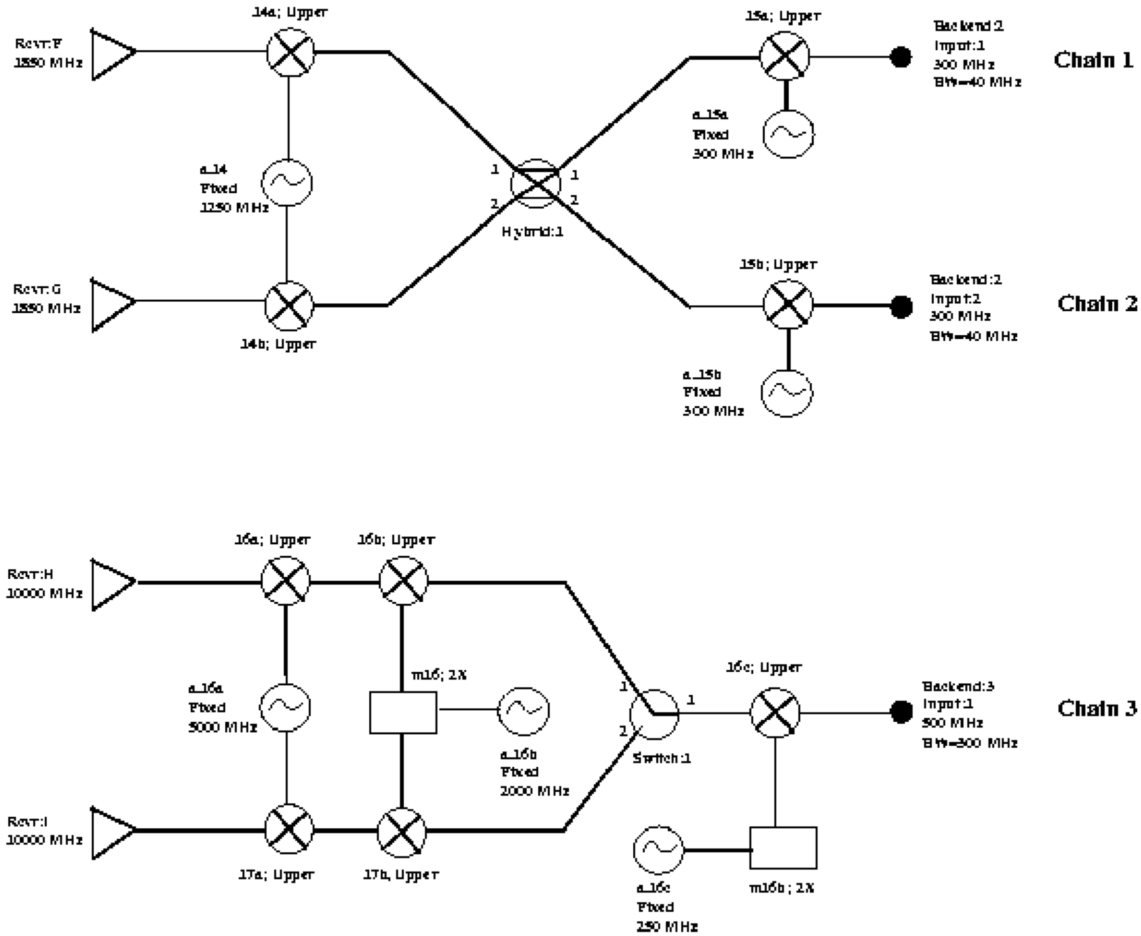

Figure 2: Three example I.F. chains, which use four receivers, that illustrate how polarization hybrids and I.F. switches can result in I.F. chains originating from two receivers.