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Overall Systems and
Performance
Tech. Notes & Reports

SWITCHING WAVEFORMS FOR THE AT RECEIVERS

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Introduction

A variety of waveforms may be needed at the AT antennas to control:-

(a) ON/OFF switches for injecting noise into the receivers for gain, polarization and T_{sys} monitoring.

(b) 0/180° phase switches to suppress interference and sampler DC offsets.

(c) 0/90° phase switches to suppress image responses.

It is hoped that by careful design of the receiver system the 0/90° and 0/180° phase switching will not be required. Nevertheless provision must be made in the design in case they are later found necessary.

The locations of these switches are indicated in the systems drawings in AT/20.1.1/015 and with important modifications in updated versions of these drawings.

Noise Switching

(1) Input

A common noise source is injected either separately into each polarization just before the LNA's or (prefereably) at 45° to the polarization axes in the waveguide immediately after the feed horns. In the latter case separate couplers set at 90° to each other will probably be required for the two bands covered by each feed.

(2) Uses

(a) Gain monitors (PSD) at each sampler and at the array "tying" point.

(b) Polarization phase monitors (phase sensitive correlators) after each sampler and before the array tying point.

(3) Required Amplitude and Waveform

Any added noise of course reduces the sensitivity of the system and its amplitude should therefore be kept to a minimum. The reduction in sensitivity is less severe if large amplitude noise sources with small ON/OFF ratios are used.

It is however proposed not to take advantage of this latter option initially in the AT because of the problems it introduces with 2 and 4 bit sampling (see section 3(d) below). Thus the noise sources will be switched with equal ON and OFF times initially but with the option of changing this later if pressing reasons to do so should arise.

The following expressions are therefore derived on the assumption of equal ON and OFF times.

(a) The degradation of system temperature ΔT_s is:-

$$\frac{\Delta T_s}{T_s} = \frac{1}{2}\,\frac{\Delta n}{n}$$

where Δn is the noise power added to a given channel and n the system noise at the same point. Thus 5% of added noise degrades the system temperature by 2½%.

(b) The error in power gain determination at the phase sensitive detectors is:-

$$\frac{\Delta G}{G} = \frac{\left[\left(\frac{n}{\Delta n} + 1\right)^2 + \left(\frac{n}{4n}\right)^2\right]^{\frac{1}{2}}}{0.5B\tau} \cong \frac{\frac{2n}{\Delta n}}{\sqrt{B\tau}}$$

For $\frac{\Delta n}{n} = 5\%$, $B = 0.5$ MHz and $\tau = 10$ sec

$$\frac{\Delta G}{G} = 1.8\%$$

(c) The error in phase determination in the switched correlators is given by:-

$$\frac{\Delta\phi}{\phi} = \frac{1}{2}\,\frac{\Delta G}{G}$$

and for the same parameters given above is 0.9% = 0.5°.

(d) Besides the deterioration in T_s due to the added noise there is also an additional reduction in sensitivity because the sampler is no longer operating at the optimum level of 0.95 RMS (Cooper 1970). For 5% added noise the levels are ≅ 0.925 RMS with the noise OFF and ≅ 0.975 RMS with it ON. In fact for ≦ 5% added noise this effect is negligible and furthermore is approximately symmetrical about 0.95 RMS and the reduction in sensitivity is identical in the ON and OFF states. For 20% added noise the sensitivities of the ON and OFF states are still approximately equal and are about 1% less than optimum. For large levels of added noise but small ON/OFF ratios either the ON and OFF states are assymmetrical about 0.95 RMS and consequently have different sensitivities or an appropriate compensation has to be made to the sampler reference levels. Unfortunately this latter compensation depends on $\frac{\Delta n}{n}$ and although ON is fixed n may vary with atmospheric conditions and observing frequency. Thus the required compensation is time variable. Although not insoluble this introduces a complexity that is best left out of the initial system. For this reason symmetrical switching will be implemented at first.

We are now in a position to estimate the amplitude of the added noise we require for gain and phase monitoring and control. For a single interferometer pair if we require a polarization error of 1% in a single integration time then the power gain in each polarization channel should be the same to within $\sqrt{2}$% (0.06 dB) in an integration time. The corresponding phase accuracy is $\frac{\sqrt{2}\%}{2}$ (0.4°).

With this gain precision the 1% polarization precision is maintained over the whole dynamic range of the resulting map. This is a more stringent requirement than need be applied for most observations. If there are in fact N elements in the array and the 1% polarization precision is required only on a partially resolved source which is the strongest in the field then the precision of gain monitoring can be reduced by a factor $(N\frac{T}{\tau})^{\frac{1}{2}}$ where T is the total observation time and τ the integration time.

Thus for N = 6, T = 12 hours and τ = 10 sec the gain and phase requirements can be relaxed by a factor ≅ 160. Such large errors cannot in fact be tolerated because the basic assumptions of small fractional errors and random gain variations would both be violated at these levels. The conclusion we can draw is that the accuracy required for gain monitoring varies greatly with the observation concerned. If we agree that we should cater for the worst case of 1% polarization precision with 2 antennas in 10 seconds and a 500 kHz bandwidth then from 3(b) we have

$$\frac{\Delta G}{G} = \frac{\frac{2n}{n}}{\sqrt{B\tau}} = \frac{\sqrt{2}}{100} = 1.4\%$$

$$\therefore \frac{\Delta n}{n} = 6.3\%.$$

Another criterion that might be used to choose Δn is the gain precision required for a given dynamic range in a map. The dynamic range is given by:-

$$DR \cong \frac{G}{\Delta G} \sqrt{\frac{N(N-1)}{2} \frac{T}{\tau}}$$

For N = G, T = 12 hours, τ = 10 seconds and a required dynamic range of 10^4:-

$$\frac{\Delta G}{G} = 2.5\%.$$

This is therefore not as severe a requirement as that set by the polarization criterion we have already used. In fact with $\frac{\Delta G}{G}$ = 1.4% the dynamic range limit due to internal gain changes alone is ≅ 2 x 10^4. Of course external gain and phase variations will impose much more severe limits on dynamic range and these must be removed using procedures such as SELFCAL.

A suitable specification for the amplitude of the added noise source is therefore ≅ 5-6% of the system noise with a 3 dB step of attenuation for observations where the accompanying increase in system temperature is more serious than gain precision. Control and monitoring of the settings of these attenuators must be provided for.

(4) Switching Frequency

Within the constraints of the components used the switching frequency should be as high as possible. In addition as there is no correlation between noise added at one antenna and that added at another the frequency can be the same at each antenna. This would not be true if too large a fraction of one noise source were radiated from its associated feed to scatter off sub reflectors, quadrupods etc. into the feeds of adjacent antennas. It is assumed at this stage that this coupling will be negligible. The extent to which this is true depends upon the directional properties of the couplers used to introduce the noise into the system.

With the above proviso I propose that all noise switching waveforms be 500 Hz square waves. In addition the switching times should be suitably delayed at each antenna so that the noise waveforms are in phase at the tying point of the array. This provides a composite noise signal for monitoring gain and polarization phase for the tied array signals.

(5) Timing Precision

Errors in gain measurement can arise as a result of:-

(a) imprecise square waves,

(b) phase shifts between modulating and demodulating waveforms and

(c) a non-integral number of switching cycles per integration time.

The errors introduced in this way should be significantly less than those due to noise statistics discussed in section 3(d), i.e. $\frac{\Delta G}{G} << 1.4\%$.

(a) Imprecise square waves

If the difference between ON and OFF times is ΔT and the full period is T then the gain error is:-

$$\frac{\Delta G}{G} = \frac{2N}{\Delta N}\frac{\Delta T}{T}$$

For $\frac{\Delta G}{G} << 0.014$, $\frac{N}{4N} = 20$ and $T = 2x10^{-3}$ sec then $\Delta T << 7x10^{-7}$ sec.

Thus the ON and OFF times must be equal to a fraction of a microsecond. Although the time resolution available at the antennas is only 1μsec intervals between clock transitions are accurate to a much higher precision. With the selected switching period of 500 Hz a switch transition will be initiated from the same clock transition in each lmsec **frame**. The equality of ON and OFF times is therefore assured to a very high accuracy.

(b) Phase shifts between modulating and demodulating waveforms

If the phase shift is ΔT in a switching period T then the fractional gain error $\frac{\Delta G}{G} = \frac{4\Delta T}{T}$.

Thus for $\frac{\Delta G}{G} = 0.014$ and $T = 0.002$, $\Delta T << 7x10^{-6}$ sec. Provided the clock and signal delays between the modulating and demodulating points are known the clock resolution of 1μsec will result in $\Delta T < 0.5\times10^{-6}$ sec which is quite acceptable.

(c) A non integral number of switching cycles

As long as the integration time is an integral multiple of 2msec this problem does not arise. In the worst case however where an odd number of ½ cycles occurs in an integration period the gain error:-

$$\frac{\Delta G}{G} = \frac{1}{2}\,\frac{N}{\Delta N}\,\frac{T}{\tau}$$

For $\tau = 1$ sec, $\frac{N}{\Delta N} = 20$ and $T = 2$ msec then $\frac{\Delta G}{G} = 0.02$. This is a worst case situation and is almost acceptable. However as stated above we avoid any problems if τ is always an integral multiple of 2msec.

Phase Switching (180°)

(1) Location of 180° Modulators

For interference suppression the 180° modulation should be applied as near to the feeds as possible. Interference entering the system after that point will be suppressed. In bands from UHF up to K band the modulator is located immediately after the LNA. Above K band the first active component will probably be a mixer and the 180° modulation can be applied to the associated local oscillator.

An additional 180° modulation will be applied to the tied array signals immediately after tying and polarization selection. At the other LBA sites only the front end 180° modulation is required.

(2) Locations of 180° Demodulators

The overall effect of synchronous modulation and demodulation is to suppress interference injected between the two operations and to remove any DC offsets in sampling and digitising. The 180° phase modulation therefore serves no further purpose after the signal has been sampled and digitized. At that stage demodulation merely involves periodically reversing the sign of the digital signal. In the CA this must be done separately at the inputs to the line correlator and the continuum correlator. Analogue signals must also be demodulated immediately prior to the array tying point.

Any modulation imposed on the composite signal after the tying point can be removed after sampling and digitizing and before recording on the VLBA recorder. For the LBA receivers the front-end modulation can be removed at this same point prior to recording.

(3) Waveforms

While signals from the antennas come through the modulation/demodulation sequence unaffected, interference injected after the modulator emerges with periodic phase reversals and the sampler DC offset alternates in sign at the modulation frequency. When similar signals from two antennas are correlated and then integrated the effects of interference and DC offsets will be essentially zero provided the modulating waveforms are orthogonal between the two antennas. The modulating waveforms must therefore be mutually orthogonal on all baselines. In addition because they must be orthogonal for all products in the correlator they must be orthogonal independent of lag. The only set of waveforms which actually meets these requirements are the set of square waves with periods related as 2^N for N an integer. The frequencies should never become equal to any fringe rate in the system or spurious responses can occur. The maximum fringe rate on the CA is 168 Hz on the 6km baseline at 116 GHz. A suitable set of waveforms for the CA would therefore be square waves with frequencies 0, 250, 500, 1000, 2000 and 4000 Hz. These can easily be generated with the existing clock system. Two other requirements should also be noted:- (a) the integration time should be a whole number of periods (i.e. a multiple of 4msec) and (b) the same waveform can be used on all bands and channels at a given antenna.

For the LBA, fringe rates can be much higher (5.6 kHz Parkes-Culgoora at 116 GHz) and it will probably not be possible to increase the switching frequency accordingly. Thus a single set of waveforms will not be suitable. The switching rates will have to be changed at various times during an observation to prevent synchronism with fringe rates. As one waveform can always be of infinite period (i.e. no switch at all) it may be convenient to make that one the tied array. This removes the need for additional 180° phase switches after the tying point. On the other LBA receivers the 180° modulation is required only at the front end and can be implemented in a manner identical to that on the CA.

If internal interference and sampler DC offsets can be controlled by other means it may not be necessary to implement 180° phase switching at all. This is more likely to be the case for the LBA than the CA because of its intrinsically lower dynamic range and possible freedom from correlated interference. If this is the case no solution to the problem of selecting suitable LBA switching rates will need to be found.

(4) Timing Precision

To be orthogonal independent of lag the 0°/180° switching waveforms have been chosen to be square waves with periods related by integral powers of 2. This relationship needs to be true to quite high accuracy and the periods have therefore been chosen so that the maximum precision of the clock is achieved in the relationship.

No special phase relationship needs to be maintained between waveforms at different antennas but it is important that propagation delays are taken into account so that the modulation and demodulation processes are in phase. In addition it is important, particularly for short integrations, that integral numbers of all switching cycles occur in an integration period.

(a) Imprecise square waves

If the durations of the 0° and 180° states differ in one antenna by ΔT in a total period T then the fractional suppression of interference or DC offset on baselines including that antenna is:-

$$\frac{\Delta I}{I} = \frac{\Delta T}{2T}$$

If we require at least 30 dB suppression then in the worst case ($\frac{1}{T}$ = 4000 Hz) $\Delta T < 0.5\times10^{-6}$. For the periods chosen ΔT will in fact be orders of magnitude better than this.

(b) Phase shifts between modulating and demodulating waveforms

As interference is only affected by the demodulation process these phase shifts have no effect on interference or DC suppression. Their effect is in reducing the correlation of signals and hence the sensitivity. If the phase shift is ΔT and we require no more than 1% reduction in sensitivity then: $\frac{2\Delta T}{T} < 0.01$. For the worst case ($\frac{1}{T} = 4000$ Hz)

$$\Delta T < 1.3 \times 10^{-6} \text{ sec.}$$

If propagation delays are taken care of correctly then the maximum error ΔT due to clock resolution is 0.5×10^{-6} sec which is satisfactory. Problems may arise as faster switching frequencies are required for example on the LBA.

(c) A non-integral number of switching cycles

In the worst case with an odd number of half cycles per integration period interference suppression is

$$\frac{\Delta I}{I} = \frac{0.5T}{\tau} = \frac{1}{500} \quad \text{for } T = \frac{1}{250\text{Hz}} \quad \text{and } \tau = 1 \text{ sec.}$$

This is just acceptable but this error can easily be eliminated by choosing integration periods which are multiples of 4 msec.

Signal correlation is also reduced by the same factor resulting in a loss of sensitivity of only 0.2% in the worst case.

(5) Precision of 180° Phase Shift

If the sum of the 180° phase shifts imposed at modulation and demodulation is not zero then some reduction in sensitivity results. For an RMS total error θ the reduction in sensitivity is $\frac{\theta^2}{8}$ and equals ~ $\frac{1}{1000}$ for $\theta = 5°$.

Interference suppression is only affected by demodulation. Thus an error θ results in suppression $\frac{\Delta I}{I} = \frac{\theta^2}{4}$. For $\frac{\Delta I}{I} < -30$ dB $\theta < 3.6°$. In most cases the demodulation is done digitally and very high degrees of suppression result. For the tied array demodulation is done using analogue switches so an error $\theta < 3.6°$ may be appropriate.

Phase Switching (90°)

(1) Location of 90° Modulators

These devices are only required on local oscillators associated with mixers with inadequate (> -40 dB) image rejection. This situation will probably only arise in the front end mixers at the very highest observing frequencies.

(2) Location of 90° Demodulators

Two procedures can be adopted here:

(a) The modulation on the signal can be removed at a subsequent mixer in the conversion chain. In this case the signal emerges with no modulation but the image has 0/180° modulation. If waveforms are orthogonal between antennas then the modulated image signals will integrate to zero in the correlator outputs.

(b) If the modulation is not removed before the correlator then products with 0°, 90° and -90° phase differences occur at different phases of the switching cycle and need to be accumulated separately and combined following phase correction after FFT. This mode requires 3 times the normal memory in the correlator and 3 times the normal number of FFT's. It has the advantage that as the demodulation is precise the phase accuracy of the 90° step at the front end can be relaxed by $\sqrt{2}$.

(3) Waveforms

The requirement again is that the waveforms be orthogonal independent of lag. They must therefore be square waves with periods related by powers of 2. There is an additional requirement imposed by the design of the modulated local oscillator that the waveforms be as slow as possible. Also at each antenna the same integral number of 0°/180° switching cycles must occur for each half 0°/90° cycle. I haven't checked if these have to be phase related but it is convenient to do so.

The above requirements are met if the 0°/90° square waves have periods of τ, $\tau/2$, $\tau/4$, $\tau/8$, $\tau/16$ and DC. The integration period τ must then be an integral multiple of 8 msec.

There is a dead period while the local oscillators are set up with the 90° phase change. To preserve the phase relationship between 90° and 180° switching and to ensure integral numbers of all switching cycles per integration period the dead period should also be an integral multiple of 8 msec. The correlator also should be blanked during these periods.

(4) Switching Precision

Similar considerations apply to the 0°/90° phase switching as to the 0°/180° switching. The waveforms however are much slower so timing precision is not so critical. We have however set a criterion of 40 dB image rejection which is more severe than the 30 dB interference rejection which affects the precision of the 0°/180° switching.

(a) Imprecise square waves

For 0° and 90° durations differing by ΔT in a period T the ratio of image to signal: $\frac{I}{S} = \frac{\Delta T}{2T}$. For $\frac{I}{S} < 10^{-4}$ and $T = \frac{\tau}{16}$ in the worst case with $\tau = 1$ sec, $\Delta T < \frac{1}{80000} = 12.5\times10^{-6}$ sec. This is large compared with clock resolution or precision but is very small compared to the dead time during phase changes. These dead times must therefore be accounted for precisely.

(b) Phase shifts between modulating and demodulating waveforms

A phase shift of ΔT results in a loss of sensitivity of $\frac{2\Delta T}{T}$. In the worst case with $\Delta T = 0.5\times10^{-6}$ sec and $T = \frac{1}{16}$ sec the reduction in sensitivity is only 0.0016%.

The image rejection is the same fraction and in the worst case is -48 dB which is more than adequate.

(c) A non integral number of switching cycles

With only one cycle per integration period in the worst case we clearly must always plan to have integral numbers of cycles per integration period. The consequences of choosing an integration time which does not satisfy this requirement by an amount ΔT is that the image rejection $\frac{I}{S} = \frac{\Delta T}{\tau}$.

For $\frac{I}{S} < 10^{-4}$, and $\tau = 1$ sec then $\Delta T < 100 \times 10^{-6}$ sec.

(5) Precision of 90° Phase Shift

For a total RMS phase error of θ between modulating and demodulating on each antenna the image rejection is: $\frac{I}{S} = \frac{\theta^2}{4}$.

For $\frac{I}{S} < 10^{-4}$, $\theta < 1.14°$.

If demodulation is done in the correlator then the front end phase switch can have errors this large. Alternatively if the errors are shared between two 90° switches on two local oscillators the error on each must be $< \frac{1.14}{\sqrt{2}} = 0.8°$.

Summary

(a) Noise switching waveform

1. 500 Hz square wave at each antenna.
2. Waveforms delayed so as to be in phase at the array tying point.
3. Noise amplitude 5-6% of T_{sys} with at least one 3 dB attenuation step.
4. ON/OFF times equal within 0.1 μsec.
5. Phase shift between modulating and demodulating waveforms less than 0.5 μsec.
6. Integration times must be an integral number of switching cycles i.e. multiples of 2 msec.

(b) 180° phase switching waveforms

1. Square waves with frequencies DC, 250, 500, 1000, 2000 and 4000 Hz.
2. All switches at each aerial have same frequency and phase.
3. No special phase relationship between waveforms at different antennas.
4. Ratios of frequencies must be 2^N to very high precision.
5. 0° and 180° states have equal duration to better than 0.5 μsec.
6. Phase shifts between modulation and demodulation less than 0.5 μsec.
7. Integration times must be an integral number of switching cycles.
8. Phase shift on modulation = 180° ± 5°.
9. Phase shift on analogue demodulation = 180° ± 3.6°.

(c) 90° phase switching waveforms

1. Demodulation can be done in the 1.8 - 2.2 GHz local oscillator or in the correlator. The latter involves an increase by a factor ~ 3 in module memory and FFT computing.
2. Demodulation in the LO imposes more stringent limits on the accuracy of the 90° phase shift (i.e. 90° ± 0.8° compared to 90° ± 1.14° when demodulation takes place in the correlator).
3. Demodulation in the LO is preferred if the specifications can be met.
4. Switching waveforms are square waves with periods ∞, τ, $\tau/2$, $\tau/4$, $\tau/8$, $\tau/16$ where τ is the integration period.
5. The 90° waveform should be phase related to the 180° waveform at each antenna. The 90° period should be the same integral multiple of the 180° period at each aerial.
6. The above requirements will mean that the integration time must be a multiple of 8 msec.
7. Dead times, in multiples of 8 msec may need to be applied during each 90° phase transition.
8. 0° and 90° states should have equal duration to better than 10 μsec.
9. Phase shifts between modulation and demodulation should be less than 3 μsec for 40 dB image rejection.