National Centre for Radio Astrophysics

Internal Technical Report

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Reducing effects of cross talk in a Radio Telescope using Walsh modulation

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Objective: To provide Technical Details, Test Results of Walsh scheme for GMRT.

Revision	Date	Modification/ Change
Ver. 1	26 August 2015	Initial Version

1.Introduction :

The signal flow chain of a typical radio telescope receiver consists of various sub-systems viz. feeds, front-end electronics, signal conditioning circuits, signal transportation to central station, baseband conversion circuits, and digital back-end receivers. For a modern radio telescope consisting of an array of dual polarized receiving antennas, there are a number of such signal chains operating simultaneously. There are strong possibilities of spurious coupling of signals from one to the other signal chains at various locations, especially at the central station where the signals from all antennas are processed together. This can cause a spurious correlation between the final signals from these different antennas. This leakage is referred to as cross talk. Since a radio telescope is a very sensitive instrument, such cross talk can seriously affect its usefulness and capabilities.

A suitable method for reducing the effect of such cross talk is Walsh modulation and demodulation scheme. A special variant of that suitable for the signal chain of the Giant Metrewave Radio Telescope (GMRT) is presented here. The suggested scheme utilizes phase modulation of the received signals using ortho-normal patterns at the front-end receiver of the antenna, and demodulating them just before combining the signals from antennas in the digital back-end. The scheme described here uses Walsh patterns to phase modulate the signals immediately after the low noise front-end circuits in the RF section of the GMRT antenna. A different pattern is used in each antenna to provide the ortho-normal basis that allows the cancellation of any cross coupled signals. The demodulation is done after digitizing the signals at Central station.

It is very important to match and align the modulating and demodulating patterns, else this can lead to loss of coherence of the desired signal. This paper describes the scheme proposed for the upgraded GMRT receivers that are currently under installation. We also present the tests carried out and the results obtained.

In GMRT there are 30 antennas with dual polarization channels from each antenna providing 60 RF signals. They are modulated using a set of 64 independent, 128 bit Walsh patterns. These patterns are generated using a CPLD based circuit at antenna base and send to the prime focus in differential mode. The pattern is used to phase modulate the signal between 0/180 degrees. At the central station, the digital backend generates the identical Walsh pattern which is used for demodulation after the digitization stage, with appropriate delay to align with the input modulating pattern. Since the delay is different for each antenna and also can change with time and with the exact configuration of the receiver chain, the value has to be determined empirically for exact alignment. We have developed and implemented a "Walsh Delay Hunting Algorithm" to determine the correct delay to be applied for maximizing cross correlation. The design is optimized for implementation in real-time on a Virtex-5 FPGA platform and is made flexible to cater to different circumstances and situations.

2. Existing Front-End Electronics :

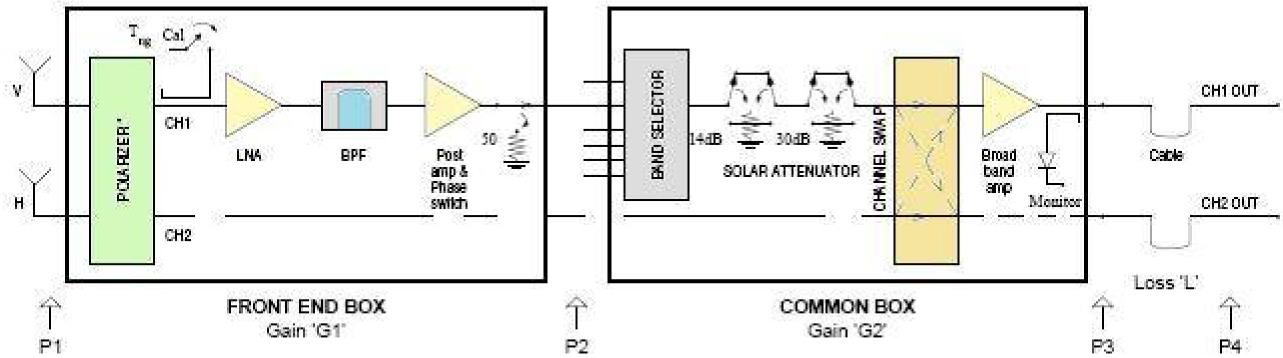


Fig 1: Schematic Diagram of Existing Front-End System

Existing Front-End system consists of multi-frequency Feed & Front-End Box with observing bands centered at 50MHz, 150MHz, 233MHz, 327MHz, 610MHz and an L-band extending from 1000 to 1450MHz and a Common Box common to all. Each multi-frequency Front-End box has two low noise amplifiers (one for each polarization), with a noise injection facility where the user can select any of the 4 values of injected noise power (Low Cal, Hi Cal, Medium Cal, Extra Hi Cal) to calibrate the gain of the receiver chain and phase switch to minimize crosstalk between different signals using separate Walsh functions for each signal path is available.

At all bands the signals go through one additional stage of amplification in the `Common Box'. The common box has a broad band amplifier which covers the entire frequency range of the GMRT. The band selector in the common box can be configured to take signals from any one of the six RF amplifiers. The common box (and the entire receiver system) has the flexibility to be configured for receiving either both polarizations at a single frequency band or a single polarization at each of two different frequency bands. It is also possible to swap the polarization channels (i.e. to make LCP come on CH2 instead of CH1 and RCP on CH1 instead of CH2), for debugging use. For observing strong radio sources like Sun, solar attenuators of 14 dB, 30 dB or 44 dB are available in the common box.

At the correlator the exact reverse phase switching is done for each antenna so that the original phase is recovered just before the cross correlation is done. Such a scheme can greatly reduce the cross-talk at all points between the RF amplifier and the baseband.

2. Walsh functionality control of Front-End From LO Synthesizer (D49 PIU MCM-2) :

All Front-End system parameters are controlled through Monitor and Control Module 'MCM-5' in the front end. All these front end parameters along with switching ON/OFF of the front end MCM are controlled at the Antenna Base Rack in the Local Oscillator Synthesizer. One of such a control of Walsh functionality can be done from MCM-2 i.e. from D49 LO Synthesizer PIU. Few of the parameters of the front end system are varied at the time of observation of a celestial source. Before analyzing the requirements for the front end control of the GMRT, it is necessary to understand what is noise calibration and Walsh switching and why are these required for the GMRT.

3. Proposed Walsh Scheme for GMRT Antennas :-

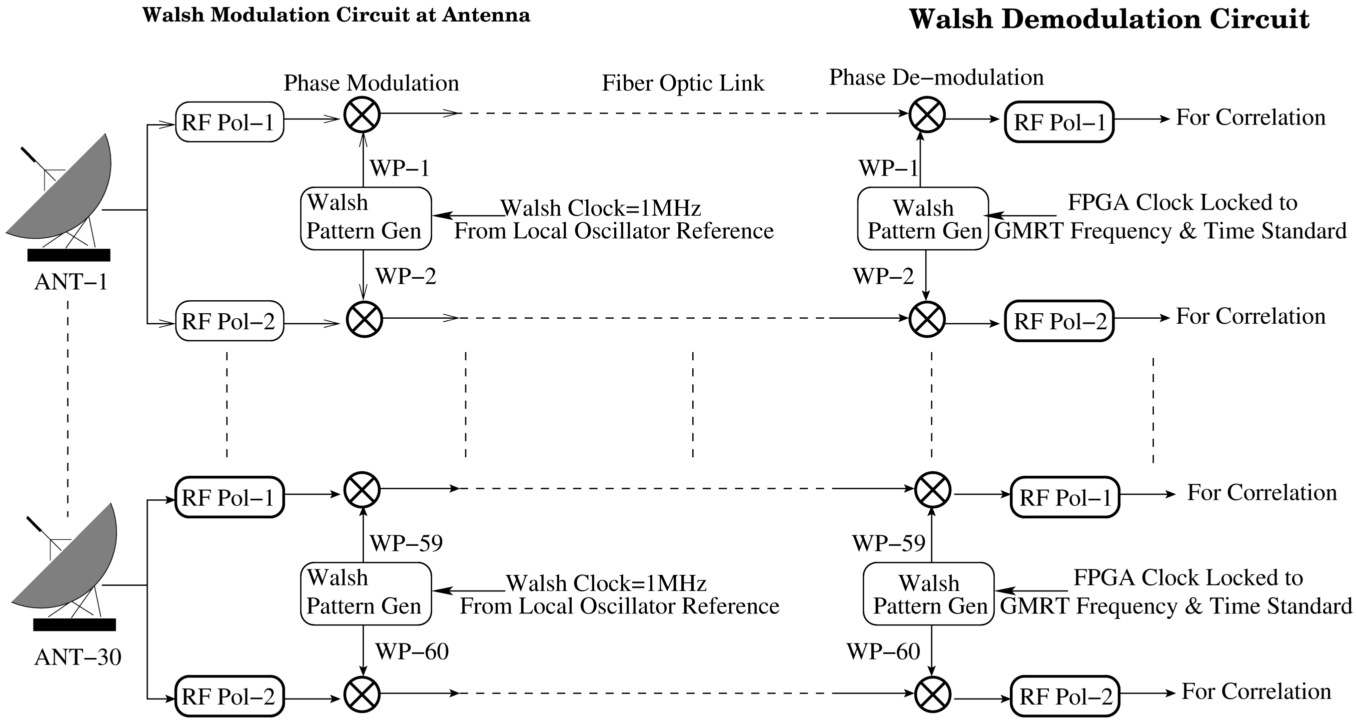


Fig. 1: Proposed Walsh scheme for GMRT

In the proposed Walsh scheme, modulation will be done in FE system using a phase modulator switch in Front-End box for each polarization. The Walsh pattern will be generated by a CPLD based Walsh card in D49 LO Synthesizer PIU and controlled by MCM-2. Each GMRT antenna will have unique walsh pattern for it's two polarizations. Hence for GMRT total 60 Walsh patterns are required. CPLD based Walsh card is designed to generate such a 128 Walsh patterns (64: Cal patterns and 64 : Sal patterns). The Walsh card functionality is controlled by MCM-2 in D49 PIU(Plug In Unit) viz. Walsh On/Off, WP-1/2 on both channels, WP-1 on CH-1 and WP-2 on CH-2.

This Walsh modulated RF signals from all antennas are then transferred via. Broad-band fiber optics system to CEB(Central Electronics Building) where they gets converted into baseband signals using a GAB(GMRT Analog Backend) system and digitized in Digital Back-End system. The Walsh demodulation is done in ROACH board (which acts as digitizer and packetizer). After finding the correct

delay between Walsh modulation and Demodulation waveform using a delay hunting algorithm then sent for correlation and accumulation.
The synchronization is achieved by locking modulator and demodulator clocks to GMRT Frequency and Time (F&T) standard.

4. Walsh Functions and pattern generation at Antenna Base:-

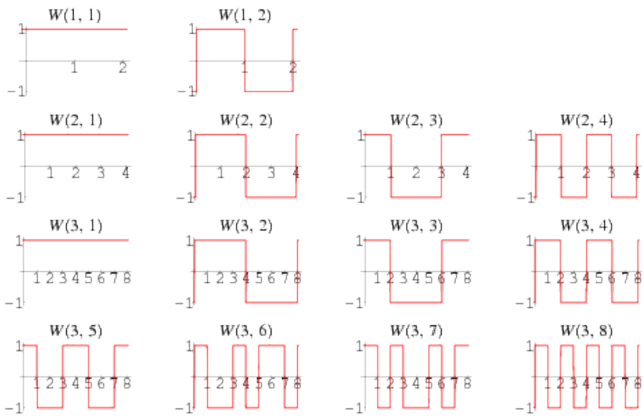


Fig 2: Walsh Patterns

Walsh functions are a series of square waves that can be combined to create almost any waveform. These functions consist of trains of square pulses (with the allowed states being -1 and 1) such that transitions may only occur at fixed intervals of a unit time step; the initial state is always +1. The function WAL(i,k) represents a waveform, known as Walsh Pattern, as a function of time k with i transitions over the period of the function defined as Sequency function. Thus, the parameter n can be interpreted as "one half the number of zero crossings per unit time. *i* is known as the normalized sequency or sequency. For an index n, *i*=log2n. There are 2n Walsh functions of length 2n. Furthermore, within the set of 2n functions there is one function of zero sequency, one of (normalized) sequency 2n−1, and one pair (odd and even) of each (normalized) sequency from 1 to 2n−1 − 1. The Walsh functions are commonly subdivided into the even functions Cal(i,k), and the odd functions Sal(i,k) which are defined by:

Cal (i,k) = wal (2i,k)

Sal (i,k) = wal (2i-1,k)

The method adopted to generate the Walsh patterns in strict sequency ordering directly from the primary set of Rademacher functions. This method has been adopted as it is simpler and requires lesser hardware resources as compared to other methods reviewed. This method generates all the i Walsh functions at the same time, where i is the index of Walsh functions. As already stated, the sequency of a Walsh function is defined as the number of zero crossings in one cycle. In strict sequency order, each row has one more crossings between 1's and -1's than the row above. Thus, alternate even and odd patterns i.e. Cal-Sal patterns are obtained in this ordering.

- **Algorithm for Walsh pattern generation :-**

  In the algorithm for Walsh functions generation, the original 1's are kept, but -1's are replaced by 0, and all the Walsh functions are generated in the complete interval between 0 and 1 rather than between -1/2 and 1/2. After the changing of original symbols the basic properties like a modulo-2 addition of two Walsh functions yields another Walsh function hold for all the Walsh functions. To generate, we use the properties.

  Step-I: Let $\overline{B}= (b_{n-1}, b_{n-2},......,b_j,.....,b_0)$ be a binary vector representing an index of the Walsh function (i.e. the sequency), where $0 \le j \le n-1$.

  Step-II: obtain the Gray code $\overline{G}=(g_{n-1}, g_{n-2},......,g_j,.....,g_0)$ from the natural binary code $\overline{B}= (b_{n-1}, b_{n-2},......,b_j,.....,b_0)$, where $gj=b(j+1)\oplus bj$ for $0 \le j \le n-2$, and $g_{n-1}=b_{n-1}$.

  Step-III: Generate the Walsh functions in strict sequency ordering as follows (i is the index of walsh patterns):
  - Some of the Walsh patterns (say WR patterns) can be obtained directly from the Rademacher functions as
    $WR(2^{i+1}-1, k) = R_i(k)$
    $W(0,k)=WR(0,k)=+1,$ *for all k*
  - Remaining Walsh functions are obtained from these WR patterns as follows:
    $$w(i)=\sum_{j=0}^{n-1} gj\, WR(2^{(j+1)}-1)=\sum_{j=0}^{n-1} gjRj$$

  While obtaining the patterns using the above equation, reduce any combinations of 3 or more Walsh functions (wherever possible) to combinations of two Walsh functions which have already been obtained in the sequence of patterns. The Cal patterns are even functions having even sequency and Sal patterns are odd functions having odd sequency. Every even indexed ($\overline{B}$ is even) walsh pattern i.e. the Cal pattern is to be complemented.

- **Advantages of CPLD based Walsh card circuit :-**
  - Consist of a programmable Walsh pattern generator: Instead of storing all the 128 Walsh patterns, Sequency pattern and noise pattern in advance, we now generate the desired pattern dynamically as per the requirements of the user. This will reduce the requirement of the resources for the operation.
  - Independent channel selection facility for taking the Walsh patterns output on any of the channels of an antenna:
    The user can now have the provision to select independent channels of a particular antenna and add Walsh patterns on these channels as follows:
    - To add Walsh pattern on one of the channels, i.e., Channel-1 (CH1) or Channel-2 (CH2) while disabling Walsh pattern on the other.
    - To add different Walsh patterns on both the channels from Group-1 or Group-2. For CH-1 or CH-2, respectively, at the same time.

- To add the CH-1 Walsh pattern on CH-2.
- To add the CH-2 Walsh pattern on CH-1.

- Variable time period selection for all the patterns: The complete 128 bits pattern for Walsh function, Sequency and the pattern for noise may be needed for certain time duration depending on the need of the user and the system. The new circuit thus gives the facility to select variable time period
- for each of the bits of these patterns. The user can select either a f_{walsh}, $f_{walsh}/2$, $f_{walsh}/4$, $f_{walsh}/8$ duration time period each bit of every pattern.
- Only CAL patterns selection: In order to remove the phase ambiguity between Cal and Sal patterns, only Cal patterns have been used for the antennae.

- **CPLD based Walsh scheme at Antenna Base Receiver:-**
  - Walsh pattern on CPLD was generated using a 1MHz clock signal which is locked to GMRT Frequency and Time reference at each antenna. This clock is further divided by a 3-stage binary counter to fundamental Walsh frequency f_{walsh} = 1MHz/4096 = 244.140625Hz (4.096mS)
  - 7 T Flip-Flops with positive edge triggering which form a binary counter to count from 0 to 127. At every low-high transition of the clock, each of the flip flops output bit is obtained forming Walsh-Rademacher patterns. After 127th counts, the counter is again reset to 0.
  - XOR Gates for performing modulo-2 summation between Rademacher patterns and other Walsh patterns. This forms the combinational part of the circuitry.
  - Two 31:1 multiplexers for selecting Walsh patterns on individual channels. The select lines for these multiplexers are the antenna selection bits through Antenna selection switch.
  - Combination of antenna selection bits is used as the input for selecting a corresponding Walsh pattern for that particular antenna.
  - Control bits are used for channel selection for the selected antenna. C5-C7 used for channel selection.

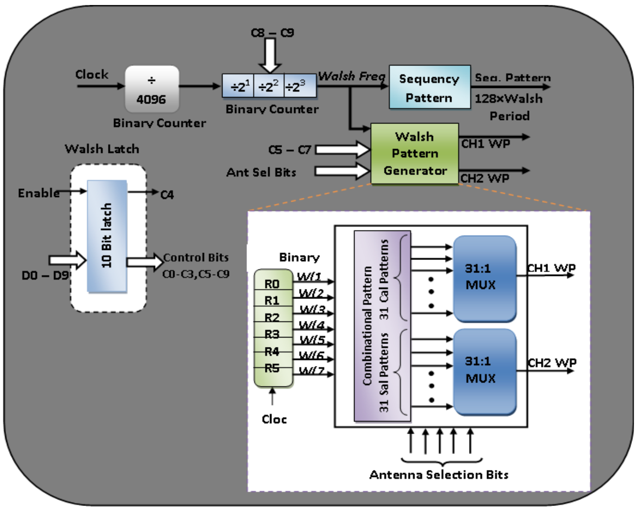


Fig. 2: CPLD Walsh card block diagram

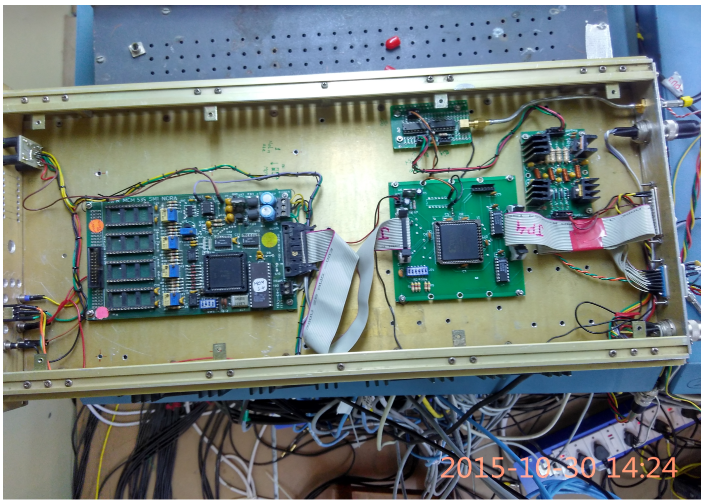


Fig. 3: MCM-4 CPLD based Walsh PIU

- **FPGA based Walsh demodulation scheme :-**

  This scheme is implemented in ROACH-1 board where digitization occurs. The scheme consists of following modules:

1. Walsh generation: Generates 64 independent, 128 bit Walsh patterns.
2. Walsh Delay BRAM: Stores selected Walsh patterns according to antenna selection from user.
3. Integer Walsh delay module: Walsh delay hunting algorithm requires this module to adjust coarse Walsh delay so as to maximize normalized cross correlation between two channels of same antenna.
4. Fractional Walsh delay module: The same is used to adjust fine Walsh delay to further maximize normalized cross correlation between two channels of same antenna.
5. Phase switcher: This module changes phase of digitized signals according to Walsh pattern to either 0° or 180°.

In this scheme generation of Walsh pattern is done same way as in case of CPLD based Walsh modulation scheme. The scheme contains extra modules to implement Walsh demodulation scheme using Walsh delay hunting algorithm.

Each ROACH board F-engine contains Walsh demodulation module which can be independently configured for any given pattern using antenna selection bits and then stored 128-bits of Walsh into Walsh Delay BRAM during initialization. Sequence pulse is used to mark start of Walsh sequence and a marker for writing Walsh pattern into Delay BRAM only once.

Once Walsh pattern gets stored in Walsh Delay BRAM then Walsh delay module (Integer & Fractional) is used to adjust delay so as to get maximum cross correlation value.

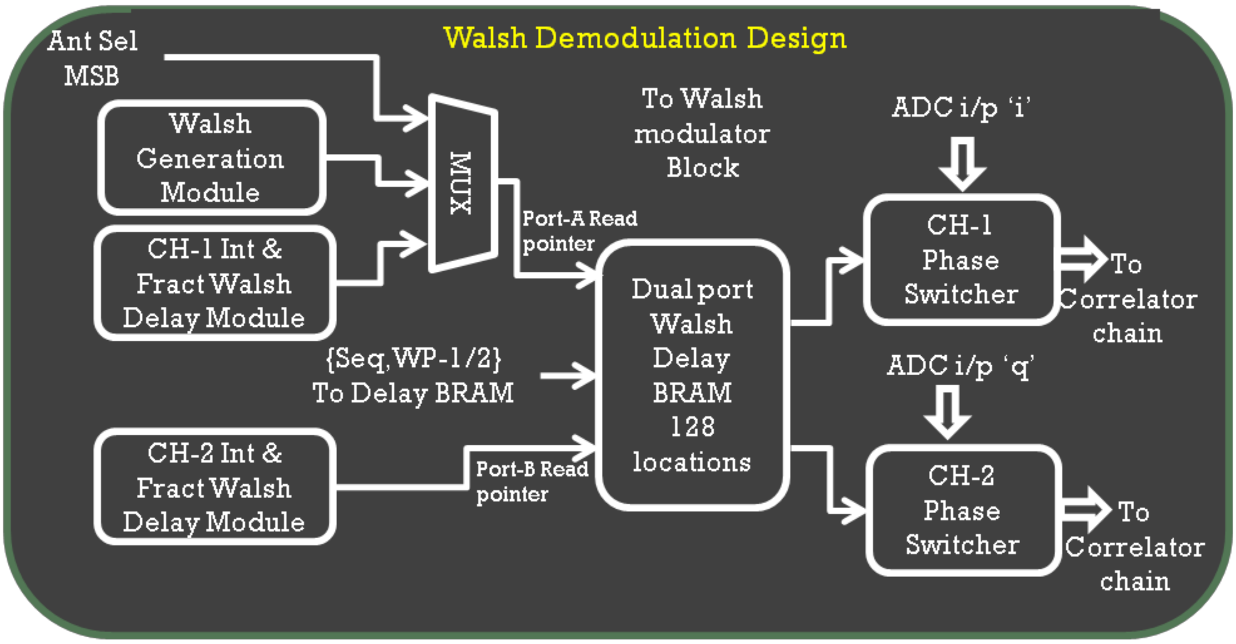


Fig. 4: FPGA based Walsh demodulator scheme

5. Walsh Synchronization :-

- **Required synchronization accuracy for GMRT*:-** The highest sequency Walsh function is a square wave is the simplest to visualize and has the most stringent requirement of synchronization. If the period of the square wave is *T*, the modulating function is +1 for *T/2* and -1 for *T/2* and the average value of the modulated signal is 0 if the signal doesn't vary over the interval *T*. The demodulating function is the same square wave and since product of two functions is identically equal to one, the demodulated signal is same as the original function and has an integrated value of ET over the period, where E is amplitude of signal. If demodulating function is not exactly synchronized and is offset by an interval *t*, the demodulated signal is +1 only for a interval *(T-2t)* while it is -1 for a period of *2t*. Thus the integrated value of the signal is now less being equal to *(T-4t)*. The noise doesn't depend on the error in synchronization and the signal to noise is reduced by *(4t/T)%*. Thus, if GMRT is prepared to tolerate a 1% loss in the sensitivity due to imprecise synchronization, the maximum synchronization error that can be tolerated will be less than *0.0025T*. The kind of switching frequencies required for GMRT imply *T* of the order of 10mS implying synchronization to within 25µS.

  For two element interferometry with each arm having synchronization error of *'t'*, the effect of synchronization error on SNR with the worst case situation is twice as large as the case for single channel i.e. worst case loss of sensitivity will be given by *(8t/T)%*. Thus with *T*= 10mS, synchronization to be about 10µS accuracy should be enough.

  In our case we chose Walsh period of T_{min}=4.096mS which corresponds to a synchronization error of 10.24µS for a 1% loss in sensitivity with single antenna Walsh modulation/demodulation and for worst case situation i.e. both antenna Walsh modulation/demodulation, it will be twice of it i.e. 20.24µS.

  Hence with T_{min}=4.096mS, synchronization error to be of the order that gives 1% loss in sensitivity is *8t/T*= 1% corresponds to *t*=0.00125T i.e. 0.00125x4.096mS = 5.12µS.

  To reduce overhead of sending Walsh sequence pulse from ABR to CEB for modulator and demodulator synchronization it is achieved by disciplining the clock of them by the GMRT Frequency & Time (F&T) standard. In case of modulator at antenna base the Walsh clock is derived from 1MHz reference frequency at CEB the same has been generated from a clock source locked to GMRT F&T standard.

- **Delay hunting algorithm :** Delay hunting algorithm is used to find Walsh delay between modulator at antenna and demodulator at central electronics building (CEB) in case of GMRT in order to maximize cross correlation. This method is less complicated and eliminates the need of sending Walsh sequence pulse back to CEB thus saving significant amount of circuitry. Both Walsh modulator and demodulator frequency is locked to Frequency and Time (F&T) standard of GMRT. At ABR CPLD Walsh modulator card uses

1MHz clock derived from Local Oscillator (LO) Reference. At CEB FPGA Walsh demodulator derives Walsh clock from FPGA clock locked to F&T standard of GMRT. All GMRT antennas have a Noise Calibration facility i.e. can inject noise in both channels at Front-End that is used to find Walsh delay using correlated noise source. The algorithm first scan complete Walsh pattern period i.e. 512mS with basic Walsh frequency i.e. 4.096mS and reduces hunting span and resolution accordingly in each iteration until normalized cross maxima reaches. It takes approx ~7 minutes to find maxima.

For the delay hunting algorithm to converge, the value of increment is restricted to 100µS. The algorithm takes 7 minutes to converge and is well accurate within 4th decimal place of normalized cross correlation value.

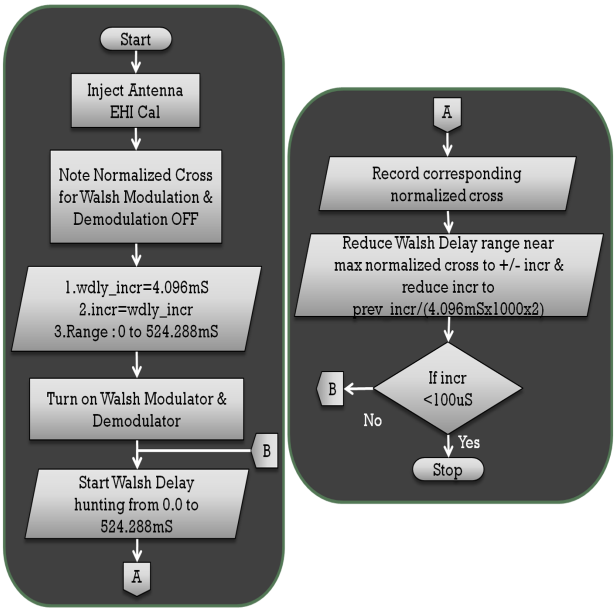


Fig 3: Walsh delay hunting flow chart

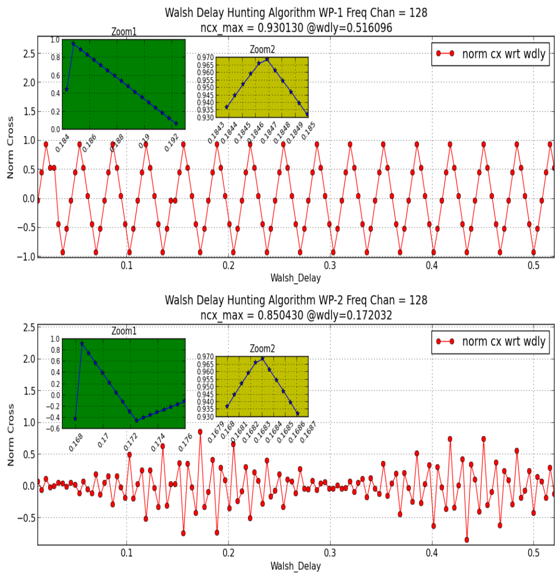


Fig 4: Walsh delay hunting plot

6. Long Term stability test :-

This test is intended to check long term stability of normalized cross after Walsh hunting algorithm. The test was carried out with a scheme where Walsh modulator clock is from LO reference i.e. 1 MHz and Walsh demodulator clock is derived from 10MHz GMRT F&T reference locked FPGA clock. The test was carried out on C10 & C12 Antennas where Noise Cal facility at each antenna was used as inputs to their two channels. Before starting of the test, Walsh delay hunting was done. The stability was tested over a duration of ~2hrs . Normalized cross correlation was found to be stable over 2hrs duration within a specified limits.

Below plots shows stability tests details :

a) First row plot is stability plot of 64th FFT channel plotted over time for both channels.

b) Second row shows from right to left columns show overlapped normalized spectral plot for C10 and C12 antenna respectively which are fairly stable over time after doing Walsh modulation/demodulation.

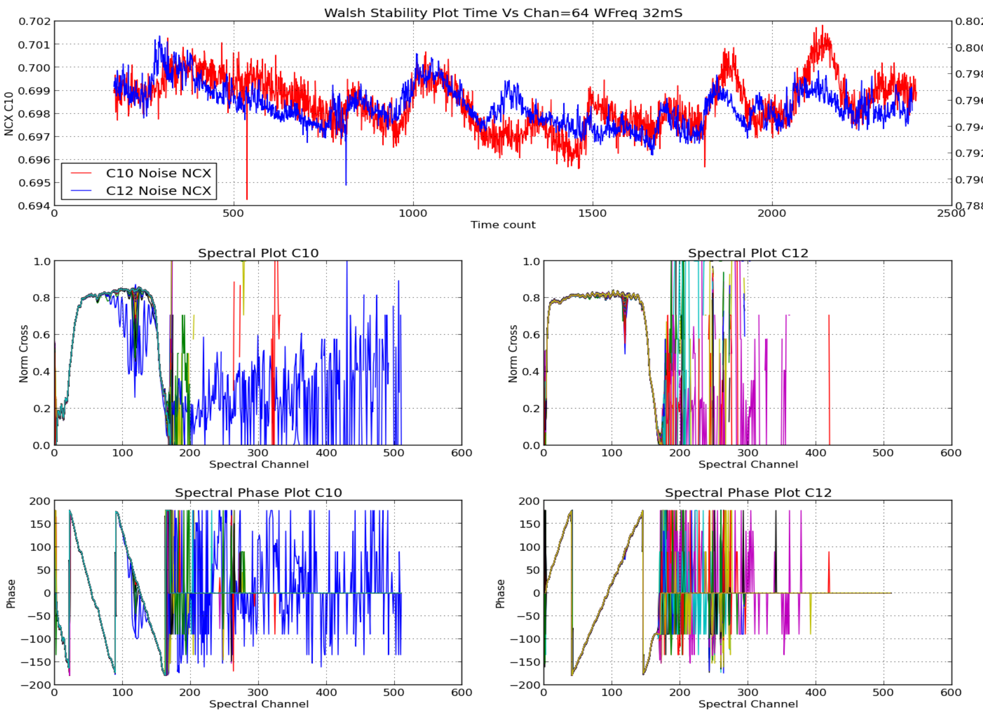


Fig 5: Stability plot for C10 and C12 antenna with Walsh mod/demod

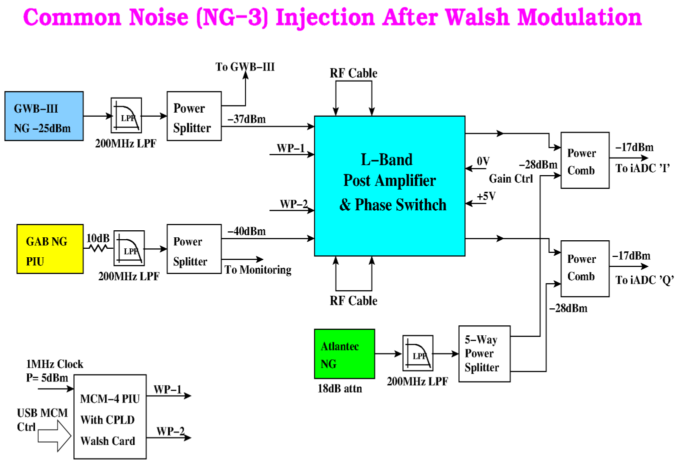
7. Effect of Walsh on Cross Talk :-

This test was intended to study the effect of Walsh on cross talk in the receiver chain of antenna to verify that it cancels out cross-talk in a receiver chain. The lab setup simulates the receiver chain behavior where we used three different noise sources as shown in *fig.5.* Three different noise sources are used to simulate to independent antenna polarization at the input of L-Band post amplifier and phase switch (L-Band PA & PS) with Walsh control WP-1 and WP-2 from MCM-4 CPLD Walsh card. The configuration of L-Band PA & PS is as shown in *fig.5.* Third noise source with equivalent power level of 3C286 (which can give normalized cross of 0.4) is injected after Walsh modulation done at L-Band PA & PS to simulate cross polar leakage. The inputs to the Pocket Correlator was maintained at a power level between -15 to -17 dBm@1.5GHz

Corresponding plots show correlation levels in first row are plots of frequency channel 64 w.r.t. Time plotted and in second row from left to right column wise plotted as follows :

a) without Walsh modulation
b) with Walsh modulation : Walsh Pattern – 1
c) with Walsh modulation : Walsh Pattern – 2
d) with Walsh modulation : Both Walsh Patterns

This experiment confirms that Walsh modulation/demodulation can reduce the effect of cross talk introduced in a receiver chain.



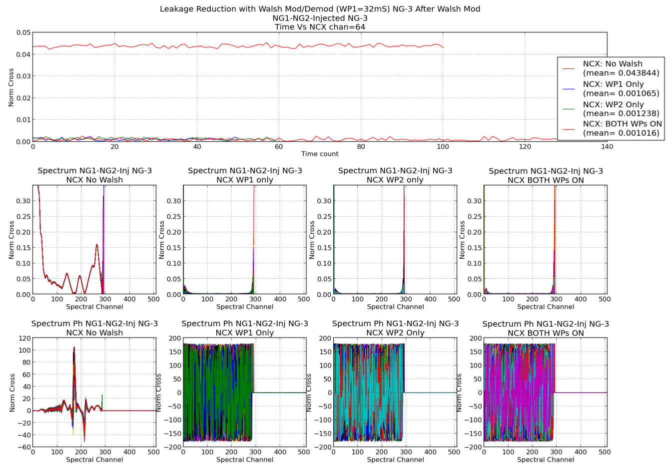


Fig 6: Lab test setup to study effect of Walsh on cross talk

8. Correlation loss test due to Walsh modulation/demodulation :-

This test is intended to check correlation loss due to Walsh modulation-demodulation. In Lab, test was done using three noise generators (NG) with NG-3 injected (simulated 3C286 source) as a common noise before L-Band PA & PS along with NG-1 & NG-2. Recorded normalized cross for following conditions with loss of correlation in each case found in brackets .

a) Without Walsh. (0%)
b) With Walsh Pattern-1 mod-demod. (~0.17%)
c) With Walsh pattern-2 mod-demod. (~0.77%)
d) With both Walsh patterns mod-demod. (~1.3%)

The plot shows normalized cross for all above cases plotted w.r.t. time for frequency channel 64. Below plots are all normalized spectral and phase plots for each of the above cases.

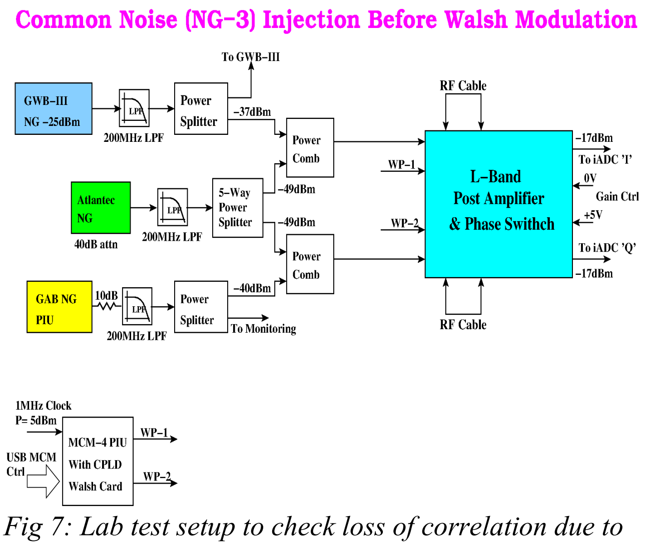


Fig 7: Lab test setup to check loss of correlation due to Walsh mod/demod

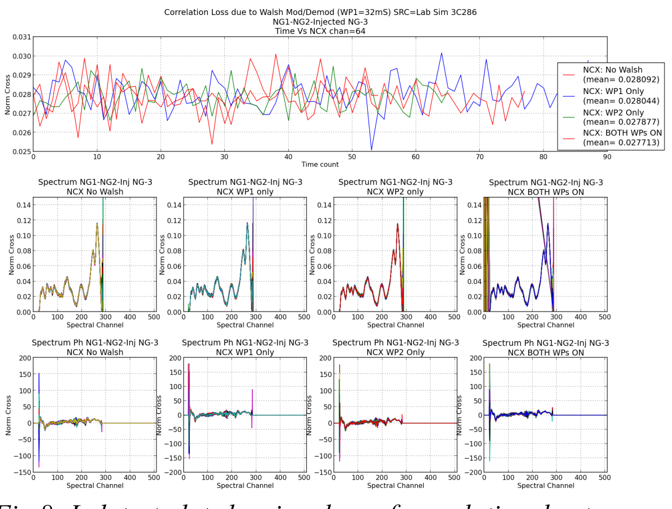
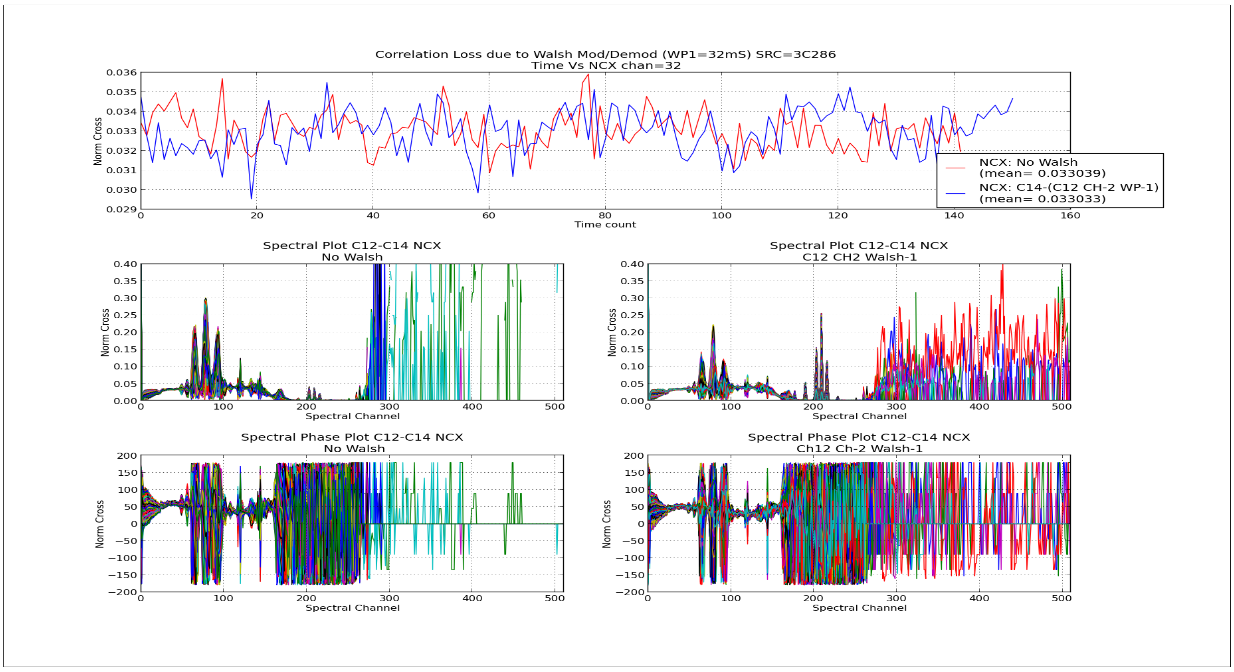


Fig 8: Lab test plot showing loss of correlation due to Walsh mod/demod

Similar tests with Walsh Pattern-1 was done with antennas(C10 & C12) where CH-2 of C12 was modulated with Walsh pattern – 1 (WP-1) and no modulation for CH-2 of C14 antenna. The correlation loss was found to be ~0.01% . Please note that here we have not applied WP-1 for both antennas unlike done in above case.



9. SOP for Walsh Testing with Antennas :

Use packetized correlator for delay compensation routine which is tried and tested.

a) Go to following directory :
   - cd /home/sandeep/Packetized_Corr/XAUI_Corr/4Ant_Corr/Ant_Test/
b) Initialization packetized correlator
   - corr_init.py config_19oct2015
c) Initialize poco walsh design without reprogramming FPGA in following location
   - cd /home/poco_function/
   - ./walsh_initV01C01.py -a 15 -d 0 -p
d) Reinitialize packetized correlator without programming
   - corr_init.py config_19oct2015 -p
e) Connect any antenna both polarization to ***roach040239***
f) Adjust power level with Noise Cal ON by tuning GAB attenuations and OF attenuations so that P_{in} = (-15 to -17dBm@1.5GHz)
g) On shivneri/lenyadri run following commands from user
   - ante 2 12 2 (Select C10 & C12 antennas)
   - cp 0;defs 0;suba 0
   - run ngon (Enable Noise Cal ON)
   - mpa 2 4 5

- comm 29;dest 17; t3V
- ana 07020x 0f020x
- st32dig(4)

  Above commands are for enabling WP-1 on only CH-1

h) Run Walsh delay hunting algorithm to find Walsh Delay for C10 and note following :
   no walsh normalized cross (nowalsh_ncx) =
   walsh delay (wdly) =
   normalized cross maxima (ncx_{max}) =

i) On shivneri/lenyadri user run following command :
   - run ngof (To make Noise Cal OFF)

j) Connect C10 pol-1 (CH-1) to 'I' input of ***roach040239***
   Connect C12 pol-1 (CH-1) to 'Q' input of ***roach040239***

k) Run delay_cal program to compensate geometric delay between antennas.
   - cd /home/sandeep/Packetized_Corr/XAUI_Corr/4Ant_Corr/Ant_Test/delay_cal_brdband/

     Before running delay update program modify source.hdr and sampler.hdr as per instruction in packetized correlator SOP
   - ./delay_update_pktized19oct2015.py -f -t- d -r -p ../config_19oct2015 –dly_offset= 0 0 0 0 0 0 0 0

l) On shivneri/lenyadri run following command from user :
   - ante 1 12 (for C10 antenna)
   - cp 0;defs 0;suba 0
   - ana 070a0x 0f0a0x (This is to enable WP-1 on both Chans of an antenna)
   - st32dig(4)

[*] Walsh Switching – Required accuracy and possible schemes by A. Pramesh Rao & C.R. Subrahmanya 25 June