

TAMKE-ALLAN OBSERVATORY

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Undergraduate Laboratory Experiments in Ku-Band Radio  
Astronomy: A Very Small Radio Telescope Interferometer

VSRT

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UNDERGRADUATE LABORATORY EXPERIMENTS IN KU-BAND RADIO ASTRONOMY

# **A Very Small Radio Telescope Interferometer**

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The authors

## Introduction

*This is a heuristic manual. The student must be ready to experiment, question and think.*

## Interferometry

This is an introductory laboratory manual for experiments in interferometry, with an emphasis on techniques useful in radio astronomy. An interferometer is an instrument that combines two signals (normally from two detectors) in a manner that the signals interfere to produce a resultant signal. The resultant signal is usually the vector sum of the two signals, but in some cases it is the product or some other mix. The traditional interferometer, usually studied and analyzed in physics courses, combines the two signals in a way that both amplitude and phase information are used. By varying the positions of the two detectors, it is possible to synthesize an effective aperture that is equivalent to the separation of the detectors and to reconstruct the impinging wavefront, thus providing significant information about the extent and structure of the signal source. The traditional phase-sensitive interferometer requires retention of the signal phase at each detector – the phase-sensitive interferometry technique will not be discussed in detail here.

A special case of the interferometer is the intensity interferometer, which performs an intensity correlation of signals from the two detectors. Although in the intensity interferometer the phase information from the two antennas is discarded, the correlation of the two signals remains useful. Aperture synthesis is not practical, but some important source characteristics may be determined.

The VSRT interferometric techniques developed here in Experiments 1-13 describe an intensity interferometer.

If the number of detectors is greater than two, then the signals of the several detectors may be combined mathematically to effectively recover some of the relative phase information from the detectors and to yield very useful results. This technique, called the phase closure technique, can produce results approaching that of a phase sensitive



interferometer. The closure phase is in theory unaffected by phase errors occurring at the detectors. It is widely used for aperture synthesis imaging in astronomical interferometry and for processing recorded signals obtained from antennas separated by large distances.

Phase closure will be discussed in Experiment 14.

## **To the student**

It is imperative that the student maintain his/her own lab record book. Buy a composition book and record sufficient information that you and your instructor can understand or recreate your setup and your results. This is an undergraduate lab manual that uses relatively few components to develop basic understanding of concepts suitable for an introduction to radio concepts of Physics, Radio Astronomy, or Ku-band Engineering.

Each experiment should be completed and understood before the next is undertaken. Each experiment record must contain name, partners, date, equipment layout, observations and findings. Findings, conclusions, and comments should follow.

## **Current web resources**

The primary reference source for the VSRT experiments is the set of memos prepared by A. Rogers and his colleagues. They may be found at [http://www.haystack.mit.edu/edu/undergrad/VSRT/VSRT\\_Memos/memoindex.html](http://www.haystack.mit.edu/edu/undergrad/VSRT/VSRT_Memos/memoindex.html)

A complimentary web resource is the larger set of Radio Astronomy resources from Haystack Observatory, entitled “Radio Astronomy Tutorial”, found at <http://www.haystack.mit.edu/edu/undergrad/materials/RAtutorial.html>

The limited bibliography at the end of this section is an attempt to select some background references that will give the student a perspective on the development of radio astronomy, in particular that associated with interferometric observations. The citations are good ones, but not very current. A more complete list of citations may be found at <http://nedwww.ipac.caltech.edu/level5/Rayburn/Rayburn4.html>

If the student has difficulty in locating a desired reference, then it may be borrowed; to this end, a comprehensive list of Astronomy-related libraries may be accessed at [http://www.cv.nrao.edu/fits/www/yp\\_library.html](http://www.cv.nrao.edu/fits/www/yp_library.html)

Finally, amateur radio astronomers can be sources of knowledge and assistance, and their activities are summarized at <http://radio-astronomy.org/>

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## Familiarization with Components

*A set of basic components will be provided. They will be chosen from currently available generic devices and may vary somewhat in operating parameters. As in life, you must be ready to question and learn.*

### Component list and function

A kit containing the components listed below will be provided. Be sure that you can identify the components shown and know their function. This kit of equipment will be sufficient for the initial set-up of a single baseline (2 dish) Very Small Radio Telescope (VSRT) interferometer.

#### Description

18"x20" DIRECTV Satellite Dish Antenna with 3 dual LNBS WNC

2-, 3-, or 4-way Ku band splitter with DC pass all ports

Several In-line amplifiers

Power injectors

CompUSA Video Grabber or equivalent, USB 2.0

12-15v AC-to-DC power supply

3-amp barrel diodes

Male-to-male "F" connector adapters

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"F" connector to BNC jack adapter

Coaxial Adapter, BNC female / RCA male

Detector diodes or pre-assembled envelope detector using high-frequency diodes, e.g. 1N6263

Coax cables with F connectors

100pt capacitor 272-123 1 Radio Shack

Compact Fluorescent Lamps

## LNB characterization

LNB is an acronym for **Low Noise Block converter**. Each receiver head normally consists of one or more LNB receiver units with its own local oscillator, mixer, amplifier and filters. A functional diagram is presented in Figure 1. Each LNB accepts signals over a broad band from about 11.5 to 13.2 GHz and this block is mixed with a local oscillator signal of about 11 GHz. Thus the output block contains a range of Intermediate Frequency (IF) signals extending from about 0.3 to 2 GHz.

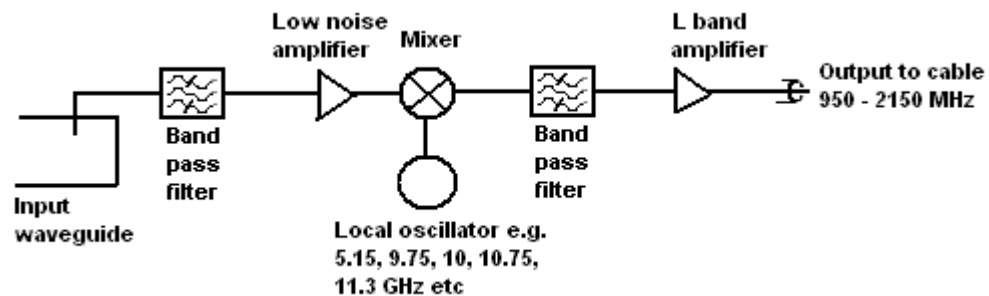


Figure 1. Block diagram of an LNB.

The LNB is the device on the front of a satellite dish that receives the very low level microwave signal from the satellite, amplifies it, changes the signals to a lower frequency band and sends them down the cable to the indoor receiver. Nominal signal frequencies are as follows in Figure 2:

Input frequency band from satellite waveguide	Input band (GHz)	Local Oscillator (LO) frequency (GHz)	Output L band frequency (MHz).
Ku band	10.7-11.7	9.75	950-1950
	10.95-11.7	10	950-1700
	10.95 - 12.15	10	950-2150
	11.45-11.95	10.5	950-1450
	11.2-11.7	10.25	950-1450
	11.7-12.75	10.75	950-2000
	12.25-12.75	11.3	950-1450
	11.7-12.75	10.6	1100-2150

Figure 2. Example Input and output frequencies of selected LNB.

Some functions of the LNB are set by the DC voltage supplied to it, normally in the range 11-18 volts. The DC voltage is fed into the coaxial output connector using a DC injector.

LNBs are designed to be able to select satellite signals according to frequency and polarization (Right Hand Circular Polarization, RCP or Left Hand Circular, LCP). This is accomplished by sending various control signals, typically the specific DC voltage level and a 22 kHz signal (present or absent) up along the coax cable to the LNB, as shown in Figure 3. Programmability options vary according to brand and model. Since the Direct TV assembly is very common, it will be presented as an example. The importance of these programming options will become apparent later in this manual where varying DC levels will be used to control LNB polarization sensitivity.

Voltage	22 kHz	Left	Center	Right
13	Off	-	-	RCP
13	On	RCP	-	-
18	Off	-	-	LCP
18	On	LCP (1178-1500)	LCP (940-1178)	-

Figure 3. Programming options for the Direct TV feed assembly with 3 Ku band dual LNBs

If one is using combined Ku/Ka Direct TV LNBS, then the following characteristics (see Figure 4) will be obtained:

Voltage	22 kHz	Far left	Left	Center
Band		Ku	Ku	Ku/ka
13	Off	-	-	IF2 (ku) RCP IF 1 and 3 (ka)
13	On	RCP IF2	-	-
18	Off	-	IF2	IF2 (ku) LCP IF1 and 3 (ka)
18	On	LCP IF 2B	LCP IF 2A	-

ka band L.O. is at 18.05 GHz

ku band L.O. is at 11.25 GHz

Figure 4. Programming options for the Direct TV feed assembly with combined Ku/Ka sensitivity.

## DC power injector

The DC injector provides power for in-line amplifiers and the LNB. As shown in Figure 5, it connects to an external power source and is isolated from the RF signal path by a high impedance inductor. The RF is transmitted through the DC injector by a coupling capacitor.

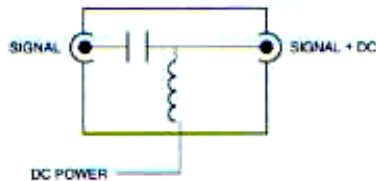


Figure 5. Schematic of a typical power injector. As shown here, the right side of the device is the upstream side.

The port of the injector labeled ‘SIGNAL + DC’ (shown in Figure 5 on the right side) must connect upstream, toward the antenna, where it will power the LNB and any in-line amplifiers. In some cases, upstream component function will be controlled by DC level and either the power supply voltage must be varied, or diodes may be connected in series with the supply to drop the voltage by approximately 0.5-0.7 VDC per diode.

Care must be taken to avoid routing DC levels to the envelope detector, which may be harmed if this occurs.

## In-line amplifier characteristics

In-line amplifiers receive DC current through the coax. The DC injector is located “downstream” of the amplifier. RF enters on the upstream side (the antenna side) and the amplified signal proceeds downstream, toward the receiver – in this case the envelope detector and the USB video digitizer.

Amplifiers may be cascaded up to the point that they begin to oscillate. Table 1 lists some typical amplifiers that you may have in your kit of parts, and the specified gain of each type.

Amplifier	Source	Cost	Gain at 1.9 GHz (dB)	Comments
Terk	Amazon	20.12	15	
CAE-9220	Amazon	7.99	25	Peaks at 1.8 GHz
ZDS-5005	Amazon	17.66	20	
15-1170	Radio Shack	36.99	15	Includes power injector
16-2565	Radio Shack	11.99	20	Same as ZDS-5005
Zenith/Phillips	Amazon	17.66	15	
RCA VHD 903	Amazon	13.89	15	
ACE 3107588	Amazon	15.51	20	

Table 1. List of some typical in-line amplifier characteristics.

## Frame grabber function

A frame grabber consisting of an analogue processor, analogue to digital converter and associated timing and interfacing components digitizes the signal from the integrator and makes it available to the driver program running in the PC.

## Envelope detector importance

An envelope detector is used to rectify and smooth the varying signal after processing by the amplifiers. It must follow the DC power injector and must be isolated from circuit DC levels. There are several possible configurations of the envelope detector, with one possible configuration shown in Figure 6.

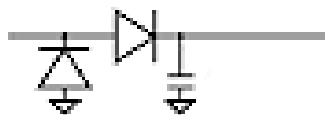


Figure 6. Envelope detector. This is one of several useful variations. The circuit rectifies and performs as a square law detector.



It is helpful to construct the envelope detector in a small box to avoid a flexible circuit with higher probability of component lead failure. Two variations of the envelope detector are shown in Figure 7. The photograph on the left shows the circuit of Figure 6, while photograph on the right shows another variation, where the grounded diode is replaced by an air-core inductor that maintains a ground-reference DC level, but preserves the (RF) analogue component.



Figure 7. Photographs of two variations of the envelope detector.

The envelope detector has several functions. First, the envelope detector conditions the signal for digitization by the video frame grabber. The high frequency L-band components coming from the signal splitter and through the amplifiers are shunted to ground, while the video digitizer responds to signals below about 5 MHz.

Second, the envelope detector has power characteristics that make it useful for power comparisons; i.e., it functions as an (approximate) square law detector. The device (as determined by the diode oriented horizontally in Figure 6) exhibits a power law that is around the ideal square law at 0 dBm but becomes greater than square at lower levels and is close to a linear voltage detector at high levels. These experiments will be performed at low signal levels for which the response is approximate square law as suggested in

Figure 8

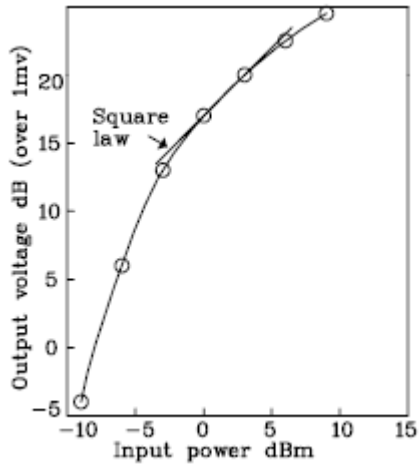


Figure 8. Power law characteristics of diode envelope detector operated at low forward voltage.

While the deviation from a square law at higher signal levels will result in errors in total power measurement and a degradation in signals to noise ratio (SNR), the error will be small on both the relative signal strengths of the fringes from a 2 detector (or more) baseline interferometer constructed as discussed in Experiment 4 and developed in succeeding Experiments.

## Software Components and Installation

*Key components of the VSRT software are the analysis code, the frame grabber driver and Java interface, and the control parameter file (used by control functions of the analysis code). For proper operation, software components must be installed on the PC by the instructor or the student according to the following procedure.*

### Frame grabber software

The function of the frame grabber is to perform a high-speed analogue to digital conversion.

Frame Grabber Software has been written to interface with the analysis program. It is much different than the standard frame grabber software. The specialized frame grabber software must be installed prior to connecting the device; otherwise industry-standard drivers will be installed and the device will not operate as intended for VSRT input. To use the new software, a USB software interface must be present. This interface is Jcomm USB API Personal Edition 1. It is available from [www.Icaste.com](http://www.Icaste.com) and must also be installed. It will permit output of the video frame grabber to be routed to the analysis software.

### Analysis and control software

Analysis software consists of a Java code that performs both signal analysis and mount control functions. Real-time data acquisition results and control parameters are presented

on the PC screen. Typical results are displayed by the graphical user interface (GUI) display shown in Figure 9.

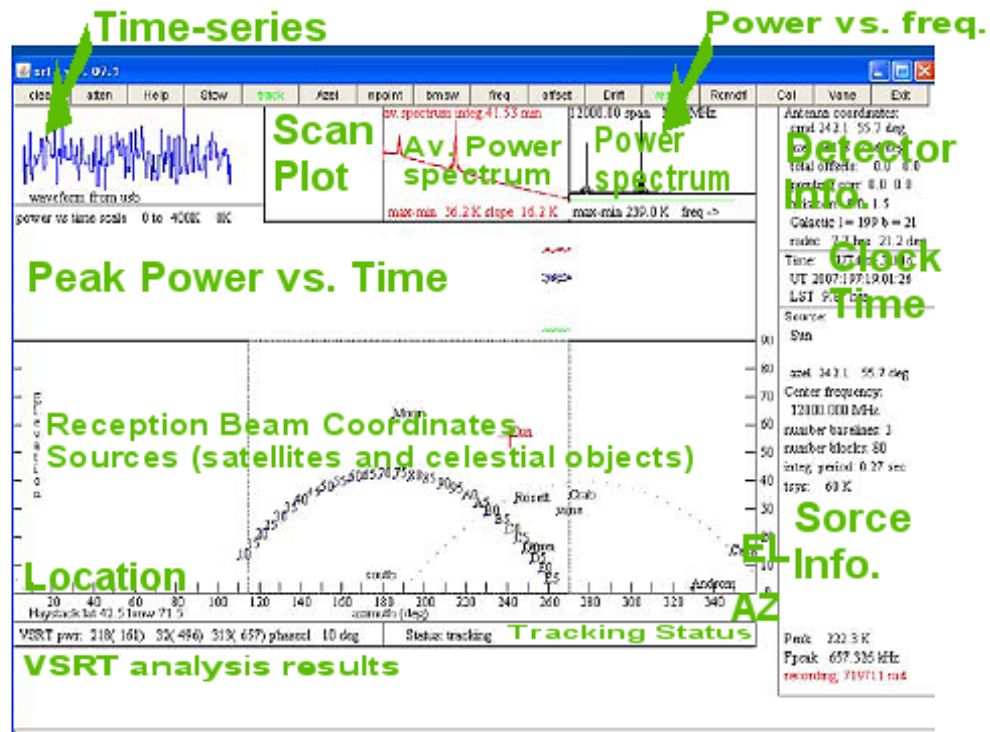


Figure 9. Analysis Software GUI explanation.

## A reference map for student measurements

The usefulness of Figure 9 will become apparent as the student performs experiments, makes measurements and interprets the results. The student must ensure that the time series data do not appear truncated or clipped. Useful frequency data will be displayed (if of sufficient power) in the Power vs. Frequency frame. This is the basic Power Spectrum display frame. The time-averaged version of this frame appears in the Av. Power Spectrum (red background) frame. Scan plots of sources will appear in the Scan Plot frame. A record of experimental results over the course of several minutes appears in the Peak Power vs. Time frame.

If tracking is in progress, reception direction (beam coordinates) will appear in the Reception Beam Coordinates frame. Site location, Tracking Status, VSRT analysis results, Detector Info, Clock Time, and Source Info Frames also appear.

## Installation of frame grabber and analysis software

*Do NOT plug in the USB frame grabber yet.* If you do, you risk loading default frame grabber drivers rather than the driver that is required for operation of the Java program.

Please take care to install the SRT/VSRT software in the **root directory** of your boot drive (normally C:\) and not in the programs directory.

1. Download the SRT/VSRT software.
2. After you download the SRT/VSRT Install.exe file, click on "My Computer" on your desktop (or in the START menu), then find the directory where the install.exe file is located and left click on the file name.
3. An install program will open and a menu driven window will appear. SELECT C:\SRTv as the directory in which to install the SRT/VSRT software. NOTE: DO NOT INSTALL THE SRT/VSRT EXECUTABLE IN THE "PROGRAM FILES" DIRECTORY
4. You will then be prompted to select the location for VSRT Icon. SELECT "On the Desktop"
5. When the Installation is complete, the SRT/VSRT installation window will remain on the screen until you click on the DONE button. There will also be a window asking you to accept a license for a MS C++ library. Click YES. A short activity of loading the C++ libraries should take a few minutes or less.
6. You should now plug in you USB frame-grabber hardware.

7. The Windows "Hardware Install Wizard" will open automatically when it detects the USB Hardware.

*Question 1:* "Can Windows connect to Windows Update to install software?"

Select: No, not at this time

*Question 2:* "What do you want the wizard to do?"

Select: Install from a list or specific location [advanced]

Under "Search for the best driver in these locations"

Check: "Include this location in the search"

Browse and enter the SRT/VSRT Install directory in the dialog box.

Example: C:\VSRT

Or whatever name you assigned. The necessary files needed by the wizard will have been loaded with the VSRT software

Click: Next

You will then see the wizard performing the file transfer. When the transfer is complete,

Click: Finish

8. You are now ready to open your VSRT console!

9. Click on the SRT/VSRT Icon now on the Desktop.

## **Control parameter file srt.cat**

The analysis code also has control functions that determine operation of the software during an observing run. The analysis code calls the file srt.cat, which provides control parameters.

Srt.cat is a text file that contains keywords to set the various options and parameters needed by the software. If a line starts with an "\*" or "#" it is taken as a comment. Two examples of srt.cat will be presented here. The first is the standard code developed at Haystack for operation in Westford, MA. This file identifies the site and operating parameters for their configuration of the VSRT.

The second example file is the file as modified for use at Tamke-Allan Observatory in Rockwood, TN.

## **srt.cat file for Westford, MA**

\* sample srt.cat file fro VSRT tests

\*SIMULATE RECEIVER - for SRT this line (with \* removed) forces

\* simulation of the USB interface to the frame grabber

\*SIMULATE RECEIVER

\*SIMULATE ANTENNA - simulate RS232 interface to antenna motors

\*SIMULATE ANTENNA -4 - simulates with time 4 hours ahead

\*SIMULATE ANTENNA 10 - simulates with a factor of 10 speed-up in time

SIMULATE ANTENNA

\*VSRT 2 1000 400 - VSRT mode with frame grabber 2 stations

\* detector\_gain\_scale=1000 plot\_scale=400

\* these parameters should be O.K. for lab demonstrations

VSRT 2 1000 400

\*SG2100MOUNT - specifies the 2-axis mount with 2 SG2100 drives

SG2100MOUNT

\*AZFEEDOFFSET 9 - specifies the feed offset of 9 degrees

AZFEEDOFFSET 9

\*STATION 42.5 71.5 Haystack - antenna\_location latitude longitude\_west name

STATION 42.5 71.5 Haystack

\* source coords epoch 1950 unless specified

\* right ascension hr mn sc declination deg mn sec name epoch

SOU 05 31 30 21 58 00 Crab

**FEBRUARY 2008**

SOU 05 32 48 -5 27 00 Orion

SOU 23 21 12 58 44 00 Cass

SOU 00 00 00 00 00 00 Sun

SOU 17 42 54 -28 50 00 SgrA

SOU 06 29 12 04 57 00 Rosett

SOU 18 17 30 -16 18 00 M17

SOU 20 27 00 41 00 00 CygEMN

SOU 00 00 00 00 00 00 Moon

SOU 00 39 00 40 30 00 Androm

\* synchronous satellite degrees\_west name

\* every entry will be plotted on the screen at its designated position

2

\* current azimuth and elevation

\* any plotted source can be selected by clicking on it

SSAT 10 10

SSAT 20 20

SSAT 30 30

SSAT 40 40

SSAT 50 50

SSAT 60 60

SSAT 70 70

SSAT 80 80

SSAT 90 90

SSAT A0 100



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SSAT B0 110

SSAT C0 120

SSAT D0 130

SSAT E0 140

SSAT F0 150

ELLIMITS -1.0 80.0 // sg2100 - limits of antenna motion

\* stow position at -1 degrees elevation

AZLIMITS 99.0 259.0 // sg2100 - limits of azimuth motion

\* stow position for SG2100 assumed at  $(99 + 259)/2$

\* the LIMITS can be adjusted to correct for mount offsets

COMM 1 /\* COM 1 \*/ - serial port for antenna control

## **srt.cat file as modified for use at TAO**

This is a portion of the srt.cat file as modified for the Tamke-Allan Observatory (TAO) site near Rockwood, Tennessee. If the control parameters are not set for the actual site of use, target acquisition and tracking will be adversely effected.

\* sample srt.cat file

\*SIMULATE RECEIVER

\*SIMULATE ANTENNA

\*DEBUG

\*VSRT 3 10000 // for 3 stations = 3 baselines

\*VSRT 2 1000 400 250 270

VSRT 2 1000 400

\*ISOCHRONOUS

\*HH90MOUNT 10.0 4.0 Sun

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SG2100MOUNT

AZFEEDOFFSET 9

\*AXISTILT 5 180 5

\* first word is key word

\* STATION: latitude longitude west in degrees

\* SAT: satellite ID then longitude west

\* SOU: source ra, dec, name, epoch

\*STATION 42.5 71.5 Haystack

STATION 35.8 84.6 TAO

\* source coords epoch 1950 unless specified

SOU 05 31 30 21 58 00 Crab

SOU 05 32 48 -5 27 00 Orion

\*SOU 05 42 00 -1 00 00 S8

SOU 23 21 12 58 44 00 Cass

SOU 00 00 00 00 00 00 Sun

SOU 17 42 54 -28 50 00 SgrA

SOU 06 29 12 04 57 00 Rosett

SOU 18 17 30 -16 18 00 M17

SOU 20 27 00 41 00 00 CygEMN

SOU 00 00 00 00 00 00 Moon

\*SOU 21 12 00 48 00 00 G90

\*SOU 05 40 00 29 00 00 G180

\*SOU 12 48 00 28 00 00 GNpole

SOU 00 39 00 40 30 00 Androm

**FEBRUARY 2008**

\*SOU 05 14 12 18 44 00 AC1

\*SOU 03 29 00 54 00 00 PULSAR

SSAT 10 10

SSAT 15 15

SSAT 20 20

SSAT 25 25

SSAT 30 30

SSAT 35 35

SSAT 40 40

SSAT 45 45

SSAT 50 50

SSAT 55 55

SSAT 60 60

SSAT 65 65

SSAT 70 70

SSAT 75 75

SSAT 80 80

SSAT 85 85

SSAT 90 90

SSAT 95 95

SSAT A0 100

SSAT A5 105

SSAT B0 110

SSAT B5 115

**FEBRUARY 2008**

SSAT C0 120

SSAT C5 125

SSAT D0 130

SSAT D5 135

SSAT E0 140

SSAT E5 145

SSAT F0 150

SSAT F5 155

\*SSAT DBS 102

\*GALACTIC 10 1 RC\_CLOUD

\*AZEL 130 12 vane

\*AZLIMITS 92.0 265.0 /\* mid az range is south \*/

\*AZLIMITS 78.0 359.0

\*ELLIMITS 5.0 175.0 /\* elevation limit south - north \*/

\*ELLIMITS 10.0 175.0

ELLIMITS -1.0 80.0 // sg2100

AZLIMITS 99.0 259.0 // sg2100

\*AZLIMITS 280 80 // sg2100 for southern hemisphere

\*ALFASPID 1.0 1.0

\*CASSIMOUNT 14.25 16.5 2.0 110.0 30.0

\*CASSIMOUNT

COMM 1 /\* COM 1 \*/

CALCONS 0.1 /\* gain correction constant to put power in units of K \*/

**FEBRUARY 2008**

\*BEAMWIDTH 7.0 /\* 3 dB antenna beamwidth in degrees - used to set offsets for scans \*/

BEAMWIDTH 4.0 /\* 3 dB antenna beamwidth in degrees - used to set offsets for scans \*/

\*MANCAL 1 /\* 0 or absence indicates automated cal vane \*/

\*NOISECAL 200.0 /\* initial value for noise diode calibration \*/

DIGITAL /\* needed for digital receiver \*/

TOLERANCE 1 /\* optional max error in counts \*/

\* COUNTPERSTEP 50 /\* optional stepped antenna motion \*/

\* RECORDFORM TAB VLSR /\* optional tabs between fields and VLSR in output \*/

\*ELBACKLASH 3.0 /\* optional correction for elevation backlash \*/

## VSRT Construction

*The VSRT is a 2 or more detector system. Signals from both detectors (LNBS with or without dishes) are combined to produce an instrument having twice the capture area of a single dish, and a resolution dependent on the separation of the antennas.*

### Configurations

An interferometer is an instrument that combines two signals (normally from two detectors) in a manner that the signals interfere to produce a resultant signal. The resultant signal is usually the vector sum of the two signals, but in some cases it is the product or some other mix.. A special case of the interferometer is the intensity interferometer, which performs an intensity correlation of signals from the two detectors.

The VSRT interferometric techniques developed here in Experiments 1-13 describe an intensity interferometer.

Initial experiments with a single LNB will be covered in Experiment 5.

### A simple VSRT – the twin LNB setup

The student should setup a simple intensity interferometer consisting of two bare LNBS as shown in Figure 10. The envelope detector is placed between the DC power injector and the USB frame grabber and is represented here as a single diode.

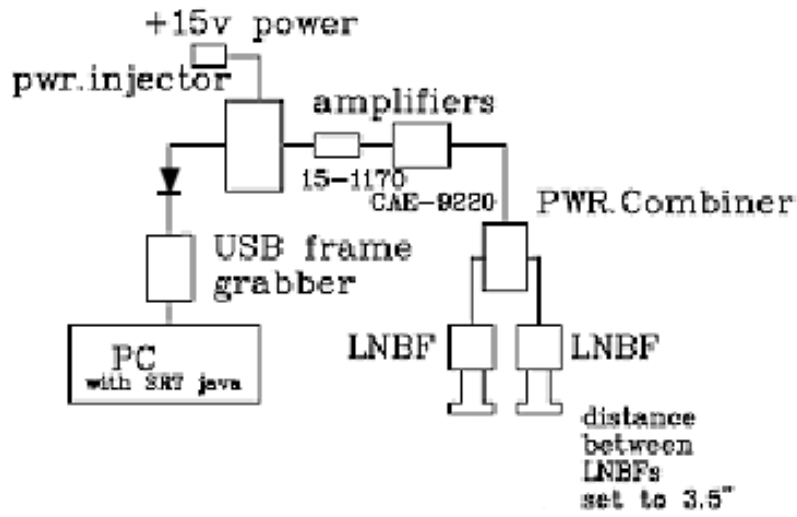


Figure 10. 2-element LNB interferometer setup for Experiment 4. Note that the diode shown represents the envelope detector circuit.

The system should be carefully constructed with all F-connectors tightened and with the components and cables affixed to a board to provide stability as shown in Figure 11.

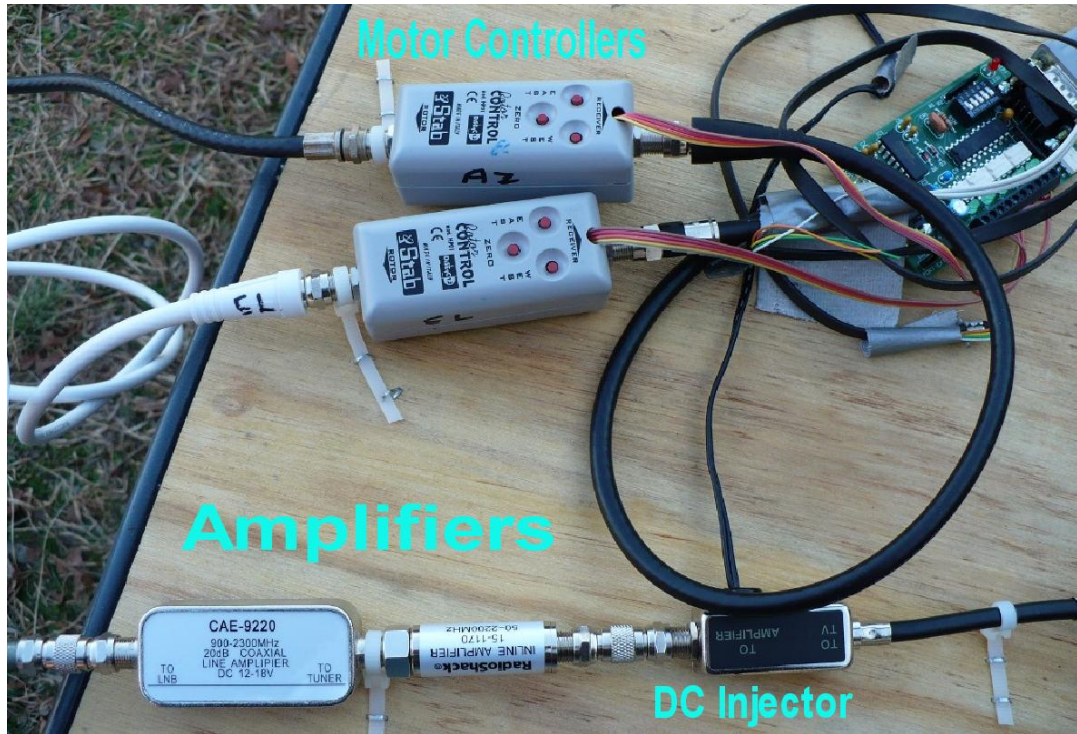


Figure 11. Components of the VSRT should be rigidly affixed to a stable platform.

## Generic VSRT configuration

A generic VSRT configuration, with parabolic dishes, twin LNBS, signal splitter, amplifiers, DC power injectors with and without diode voltage offset, a low pass filter, the envelope detector, the USB video frame grabber and the PC, is presented in Figure 12. In general the student will use a combination of the components shown here. Component functions are described in Experiment 2.



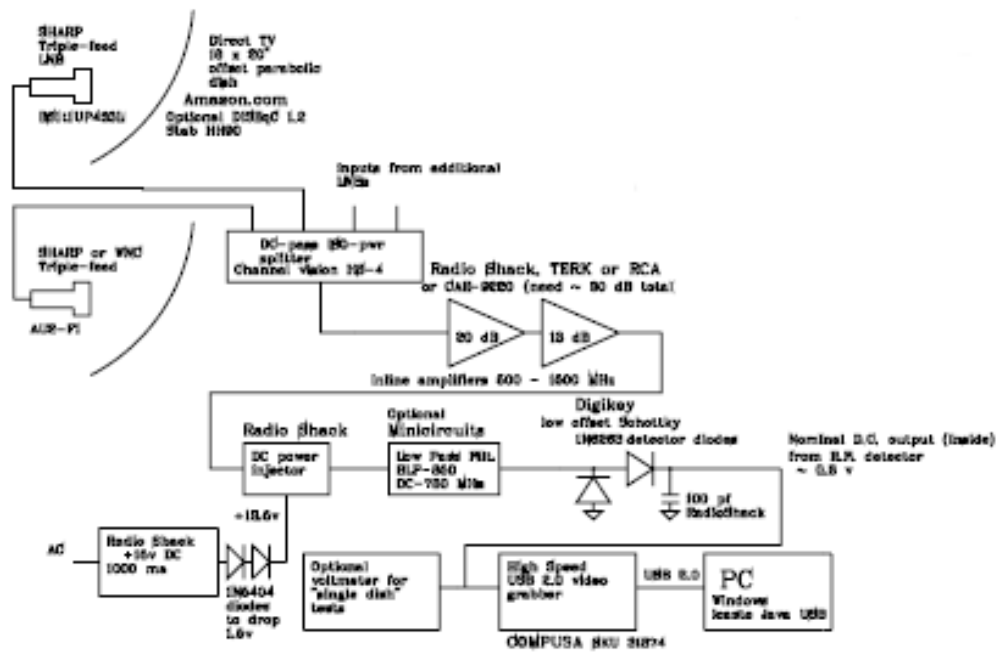


Figure 12. Generic VSRT Block Diagram. Please see text for a discussion of components.

## Interpretation of VSRT Output

The VSRT analysis software performs several functions and generates displays of results. In general the output appears as shown in Figure 9.

## Generic Source Characterization

*A variety of sources will be used to simulate radio astronomy measurements.*

### Examination of 2 unmodulated sources

The simplest test of the VSRT interferometer is to point one feed (or dish) at the other. The experimental setup should be that of Figure 10 shown in Experiment 4. In this, both LNBS will share the same noise. This noise correlates the output of both LNBS and hence produces a large signal at the splitter.

With the very large bandwidth of the LNB intermediate frequency (I.F.), the correlation will average to zero over frequency for any substantial separation of the feeds unless the splitter output is passed through a narrow band filter. Figure 13 shows the amplitude vs time (time series) signal and the frequency spectrum for 2 LNB feeds facing each other.

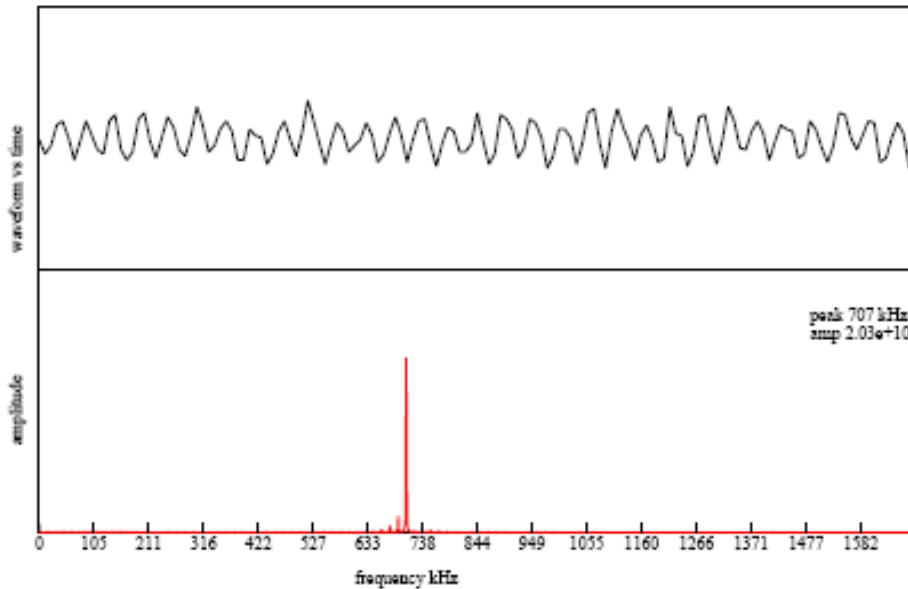


Figure 13. Time series plot and frequency plot with LNB feeds pointing directly toward each other. The frequency shown, 707 KHz, is the difference frequency between the two local oscillators.

## A fundamentally important measurement

This is a fundamentally important result, in that it demonstrates that if both detectors (both LNBS) see the same noise, then this noise will correlate the output and the output frequency spectrum will show a peak with a frequency equal to the difference frequency of the local LNB oscillators.

## Examination of a single unmodulated source

Another useful test source is the signal from a fluorescent lamp. A circle lamp or spherical bulb is most useful as it provides a small diameter source. The frame grabber electronics combined with a few seconds of integration is sufficient to detect the lamp at a distance of several feet from the feed and at much larger distances if the dish is used along with the feed. Figure 14 shows the signal from a fluorescent circle desk lamp at a distance of about 2 feet from each feed. Fringes are too weak to be seen in the time series data but can be clearly seen in the fringe rate spectrum.

The frequency detected and shown here is the difference frequency of the correlated noise from the LNBS. The source is considered unmodulated because the modulation frequency (60 Hz, yielding 120 pulses per second) is far below the minimum frequency detected by the Java software analyzer.

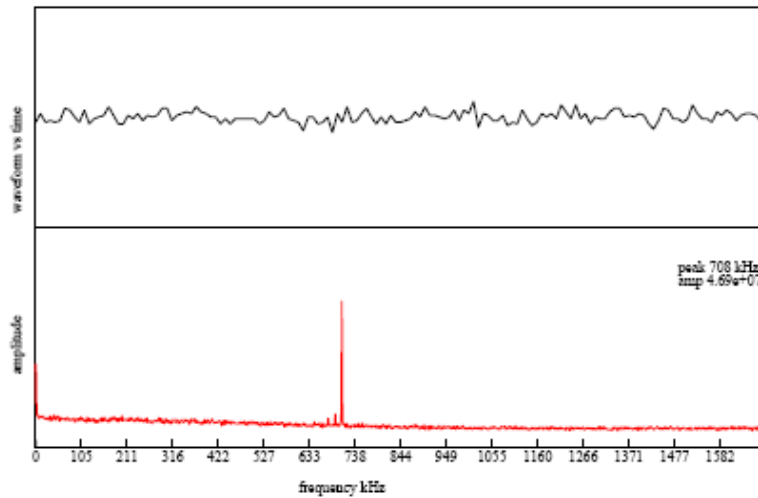


Figure 14. Fringes from a circle (Circline) lamp examined with 2 LNBS in the standard interferometer configuration. A linear fluorescent lamp would give a similar pattern.

## Examination of a single modulated source

A spiral fluorescent lamp (A&H CF20/S/41K) or Compact Fluorescent Lamp (CFL) is more compact than a Circline lamp and it is a good test source, although there are some unwanted modulation spurs in this lamp around, 90 kHz. The student should examine the output of a CFL using the VSRT.

## Student measurements

Record the local oscillator difference frequency that you detect with the two LNBS facing each other. This is the frequency that you will see as you examine an unmodulated source.

Examine the spectrum of your CFL lamp with one dish pointed at the CFL and the other dish pointed away. Record this as the frequency of your CFL lamp. This measurement must be made after the CFL has operated for 5 minutes. There also will be changes in this frequency as the lamp ages. CFL lamps will be discussed briefly here and considered more deeply in Experiment 6.

Some CFLs exhibit a periodic variation in RF output with a period of perhaps 5s. If you have such a lamp you may choose to try a different one, or compensate for this variability. Interestingly, the variation does not appear very much in the visible power output. You should verify this.

Configure your equipment so the LNBS both see the same incoherent source (a nearby CFL). What are the signals that you detect?

Configure your equipment so the LNBS face each other but both see the CFL lamp. What are the signals that you detect?

## CFL Parameterization

*Your reference sources for many Indoor Lab Experiments will be Compact Fluorescent Lamps (CFLs). You will find them useful and interesting.*

### Lamp construction, modulation, and instability

In the 1950s and 1960s radio astronomers often used gas discharge tubes mounted inside the receiver waveguide to calibrate the radiometer. In simple terms, the gas discharge results in a plasma of electrons which is optically thick to microwaves. The noise temperature output is equal to the electron temperature, which is typically around 10,000 K. The modern energy saving bulb, currently available in the supermarkets, is a high intensity discharge (HID) in mercury-vapor. The lamps are mostly made in China and probably are pretty similar from one brand to another. The most common brand is GE and the discharge tubes are either helical or loop up and down. Wattage ranges from 15 to 30 w (equivalent light output to about 50-100 w incandescent). The electronics in the base produce a high starting voltage (most likely around 1 kv) generated from a frequency (derived from a transistor oscillator) in the range of 50 to 90 KHz. The high frequency is used to reduce the 120 Hz flicker. There are two problems associated with the use of these lamps for VSRT tests, demonstrations and experiments:

- 1] There is often a 50-90 KHz modulation of the microwave output that can be confused with the modulation produced in the detector by interferometric fringes.
- 2] There is often a variation in the microwave output with a period of perhaps 5-15 seconds. This may disappear when the lamps are operated for a while and become more stable.

Both of these problems appear to be a minimum in the large lamps. The GE Biax electronic 27 W 120 VAC 60 Hz 400 ma FLE27QBX/2/SW gave the best results. Alan Rogers measured a brightness temperature of about 5000 K for this lamp, but the brightness temperature in the RF portion of the spectrum can appear to be much

higher. The tubes appear to be optically thin at 12 GHz so the maximum output occurs when the tubes pointed towards the antenna.

## **Student measurements – single base and single source**

Setup 2 LNBS (2 feeds) 6.5 cm apart and single fluorescent lamp initially about 30 cm away from the VSRT as shown in

Figure 15(a). Measure the correlation vs distance and angle. Make plots of the correlation vs distance and angle. The distance dependence should follow the inverse square law and the angle plots will trace the feed antenna pattern. With the lamp at 50 cm vary the distance between the feeds and measure the correlation vs the feed separation.

The lamp may be modeled as a source of 5 cm diameter, which equals 0.1 radians at 50 cm. The student should become aware that placing a photoflood reflector shield around the lamp will increase the source intensity for some experiments. This will also, however, widen the diameter of the source and experiments requiring a small source will become more difficult to interpret.

Consider that the interferometer resolution theoretical resolution for the 6.5 cm separation at the wavelength of 2.5 cm (12 GHz) is 0.38 radians. Thus the source is unresolved and you cannot see much dependence in signal power with variations in lateral position of the source (source azimuth). Demonstrate this.

As the LNB separation is made greater and baseline approaches 25 cm, the source will become resolved. You can move the source and see signal fringes on the long-term intensity plot. Measure this.

## **Student Measurements – single base and complex source**

Replace the single CFL with two CFLs. The feeds are polarized as can be demonstrated by reflecting the signal from the lamp off a metal sheet as illustrated in

Figure 15(b). This will reduce the correlation, which can be brought back by reflecting the signal into both feeds as shown in

Figure 15 (c)

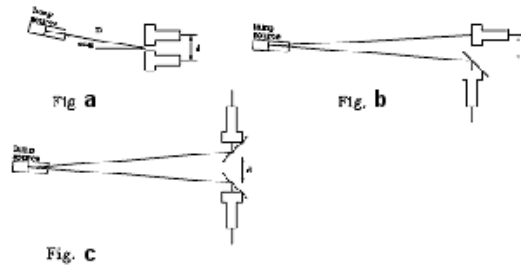


Figure 15. LNB configurations in single-source interference experiments.

## Student Measurements – complex base and complex source

The SRT software (in VSRT mode) can analyze the fringe phase from 3 baselines to form the closure phase. The closure phase concept, which is discussed in Experiment 15 can be demonstrated by placing 3 feeds close together to form a triangle of baselines. When the lamp source is turned on fringes should be observed at 3 different fringe rates. The fringe rates should exhibit a simple arithmetic relation within the experimental noise. The student should demonstrate this. The student should also show that this relation (phase closure) does not occur if two lamps are used to produce an asymmetric double source.

## Single Dish Experiments

*The VSRT has maximum utility when operated as an interferometer; nevertheless, single dish measurements can be very instructive.*

### Sensitivity to sources

A satellite finder may be used to convert output of a single dish to a power level specified on a meter and (typically after exceeding a present detection threshold) to provide an audio indication of detected power.

Single dish experiments can be done with the VSRT by disconnecting one of the LNBS from the antenna splitter and using a modulated source, such as a CFL.

### Exploration of LNB sensitivity

Use a single LNB (not mounted on a dish) to demonstrate the modulation peak of a single CFL. Plot the acceptance angle of the LNB as the source is moved across the aperture of the LNB. Quantify the sensitivity with angle and with distance from the LNB to the CFL. Determine the half power points on the plot (3 dB points) by using a 2x splitter to determine reference half-power values.

### Exploration of dish/LNB sensitivity

Mount the LNB on a dish and again demonstrate the modulation peak. Quantify the sensitivity with angle and with distance from the dish to the CFL. Determine the half power points on the plot (3 dB points) by using a 2x splitter to determine reference half-power values. For maximum signal, you may need to reset the DC power voltage to the LNB, since the level of the voltage selects whether the LNB is sensitive to Right Hand Circular (RHC) or to Left Hand Circular (LHC) Polarization.



## LNB programmability options

LNBs are designed to be able to select satellite signals according to frequency and polarization (Right Hand Circular Polarization, RCP or Left Hand Circular, LCP). This is accomplished by sending various control signals, typically DC voltage level and a 22 kHz signal up along the coax cable to the LNB. Programmability options vary according to brand and model. Since the Direct TV assembly is very common, it will be presented as an example.

The Direct TV feed assembly with 3 Ku band dual LNBs has the following characteristics as presented in Figure 16

Voltage	22 kHz	Left	Center	Right
13	Off	-	-	RCP
13	On	RCP	-	-
18	Off	-	-	LCP
18	On	LCP (1178-1500)	LCP (940-1178)	-

Figure 16. Programming options for the Direct TV feed assembly with 3 Ku band dual LNBs.

In this table, the Left LNB unit is on the left side, looking at assembly with feeds pointed toward the observer and with connectors below. RCP/LCP or RHCP/LHCP denotes the circular polarization “handedness” after reflection from the dish (i.e. polarization in sky).

## Determination of polarization sensitivity

The CFLs may be used to generate circular polarized Ku signals and this signal may be used to analyze performance of the LNBs. The experiment will ‘work’ for a single dish (if a power detector or satellite finder is used) or in the standard VSRT configuration. A simple experiment to demonstrate that the VSRT or two LNB feeds are sensitive to circular polarization can be set up using a 27 W fluorescent lamp (FLE27QBX/2/SW) as a signal source to generate fringes between 2 feeds spaced right next to each other. If the lamp is temporarily covered with an aluminum beverage can, whose top has been cut away with scissors, the fringes will completely disappear. Weak fringes can be made to remain when the lamp is covered if a helix antenna of the correct hand sense is placed through a small hole in the base of the can as illustrated in the photos of Figure 17.

Measurements must be made rapidly to prevent overheating of the lamp.

Putting the helix inside the can creates an analyzer that can determine the **sense of polarization produced by the CFL**. With the voltage to the power injector at 13v, only the left-handed helix will typically produce fringes. A straight wire can pick up the noise signal from inside the can and convey the signal to the LNB outside.

If the helix is extended through the can, the **sensitivity of the LNB to polarization** can be determined more dramatically. Used in this way, it can easily be shown that for certain voltages the LNB is sensitive to right hand polarization (RCP). Reflection on the dish reverses the sense of polarization.



Figure 17. Cans should be chosen to fit over the CFLs and they should be labeled LHC and RHC to facilitate measurements.

Another way the experiment can be conducted is to cover the lamp with a can and an exposed helix and then change the voltage from 13v to 18v, noting that fringes on the LCP helix will appear and disappear as a function of voltage. Recall that the sense of polarization will change as the signal is reflected from the dish.

## Single dish radiometry measurements

If a single LNB is connected to the detector (via a single CAE-9220 amplifier), the output from the detector can be observed with a digital multimeter (e.g. Radio Shack model 22-813 or a USB data logging meter such as Fluke model 189).

Typical readings (with detector output loaded with frame grabber) are as shown in Figure 18.

Outside pointed at sky	4 mV
Outside pointed at ground	20 mV
Outside with hand over feed	24 mV
Inside	24 mV
Inside with hand over feed	24 mV
Inside with 27 W fluorescent lamp 1 foot away	50 mV

Figure 18. Typical readings at envelope detector output with 75 ohm load. A 1000 ohm load should increase voltage levels by a factor of about 8.

## Radiometry Calculations

The LNBS are sensitive to radio waves at 12 GHz or a wavelength of 2.5 cm. The power output, P, can be characterized by the sum of 2 terms.

$$P=g(T_R+T_A)$$

where

g = amplifier plus detector gain

TR = receiver noise temperature in Kelvin

TA = antenna (or feed) noise temperature in Kelvin

The antenna temperature is given by the equation of radiative transfer

$$T_A = T_I e^{-\tau} + T_p (1 - e^{-\tau})$$

where TI = the input temperature

Tp = the physical temperature of the medium through which the radio waves propagate

τ = medium opacity

When outside pointed at the sky

$$T_A \sim (3+5)K$$

where 3K is the cosmic background and 5K is the noise picked up in the propagation through the atmosphere.

When pointed at your hand or the ground

$$T_I \sim 300 K$$

When inside a room the radio waves emitted from the objects in the room all come from opaque objects (or reflective objects) at room temperature.

When outside, one may see the large power increase from the detector when the dish is pointed at the ground. There is a power increase by about 50% when the dish is pointed at the Sun<sup>1</sup>.

Verify the above discussion by making measurements and comparing results. You may decide to use an opaque absorber that subtends an angle of about 0.5 degrees and to calibrate your system to measure the temperature of a distant object that subtends an angle of 0.5 degrees.

## Double Antenna Experiments

*A serious VSRT is a twin-antenna system for examining celestial sources. Signals from both antennas are combined to produce an instrument having twice the capture area of a single dish, and a resolution dependent on the separation of the antennas.*

### Celestial sources

Experiment 4 introduced the basic elements of the VSRT. The consideration of celestial sources raises the challenges of achieving sufficient sensitivity for detection and analysis; providing stable mounting for acquiring signals and documenting results; ensuring tracking to permit longer study periods and integration times; and learning calibration and analysis techniques that extend basic measurements and suggesting extensions.

### Calibration of the 2-element interferometer.

Experiment 13 will explore solar scans by varying Elevation and Azimuth, and an absolute determination of solar temperature in the Ku band. In this Experiment we will perform a simple radio astronomy experiment to calibrate the temperature of the sun using a vane absorber. This vane needs to be in the far field of each dish and to be unresolved by the interferometer.

### Intensity function of relative temperature

A 12" diameter absorber at 115' subtends an angle of 0.5 degree. This absorber can be used to calibrate the fringe amplitude, and is close to the same angular size as the Sun. Signal intensity is a linear function of temperature, thus we have

$$T_{\text{sun}} = (A_{\text{sun}}/A_{\text{vane}})T_{\text{vane}}$$

where A = intensity amplitude

T = brightness temperature.

## Measurements of relative temperature

Calibrate the interferometer using a distant absorber (wood or conductive foam) of the dimensions and distance discussed above. Perform a temperature measurement of the sun and the moon and discuss your results.

## Correction for beam filling fraction

In many cases it is impractical to construct a vane of the same angular size as the source, thus the relative area must be used as a correction factor. For example, suppose a vane of 8.5" in diameter is located 285" away from the interferometer so it subtends an angle of 1.48°.

Suppose that the measured amplitudes were

Sun: 443

Vane: 33

Then the calibrated temperature of the Sun is found as follows:

$$\text{Solar Temperature} = (443/33) \times 300\text{K} \times (1.48/0.5)^2 = 35,000\text{K}$$

## Student filling fraction measurement

The student should make the preceding measurement and implement corrections for sky and LNB temperature. Sources of errors should be accounted for, including the following, showing rough estimates of the errors:

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- 1] Noise in the measurement  $\sim 5\%$
- 2] Imperfect absorption in the vane due to reflections  $\sim 5\%$
- 3] Non linearity in the square law detector  $\sim 10\%$

## Nulling a Complex Source

*A simple double-source experiment will demonstrate the phase sensitivity of the VSRT in 2-detector configuration. Counter-intuitive results can be most instructive.*

### Experimental setup

For this experiment it is better to choose lamps (CFLs) that are stable, i.e., their radio frequency (Ku band) output must be relatively constant in time. If this is not possible, then intensities should be monitored and recorded as the most intense value within a CFL cycling time.

The student should set up two LNBS with about 15 cm separation, center to center, as shown in Figure 19. Two CFLs should be used as sources, separated by about 2m from the LNBS and the spacing between them chosen so that the signals from each cause interference; i.e., so they are in the first null of visibility as seen by the LNBS.

A schematic of the experimental setup is presented in Figure 20. It is important to monitor the total power at the output of the envelope detector using a voltmeter as shown in this figure.

### Total Power Measurements

In the configuration of Figure 19 and Figure 20, it will be seen that turning one lamp off decreases the total power observed by the voltmeter across the power detector but INCREASES the fringe power as can be seen in the VSRT display of the fringe power vs time.

The student should demonstrate this effect by monitoring and sketching or photographing the VSRT display, and by annotating the variation of total power as shown by example in Figure 21.





Figure 19 Laboratory setup for Experiment 9.

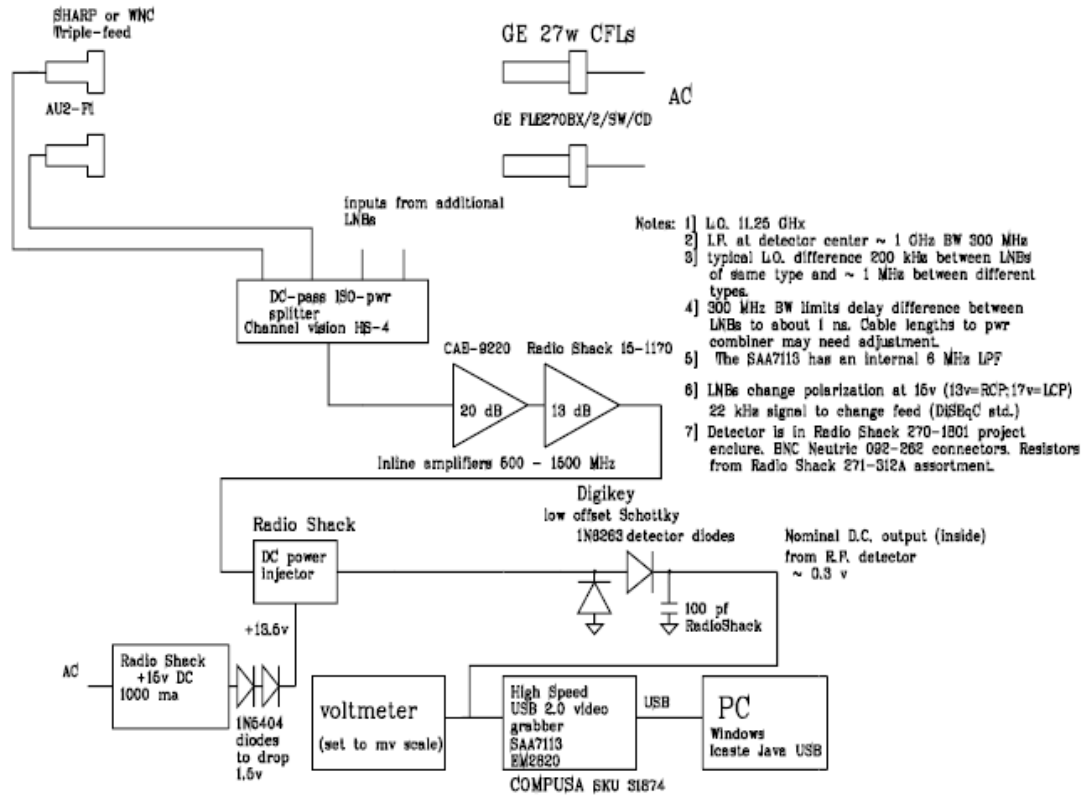
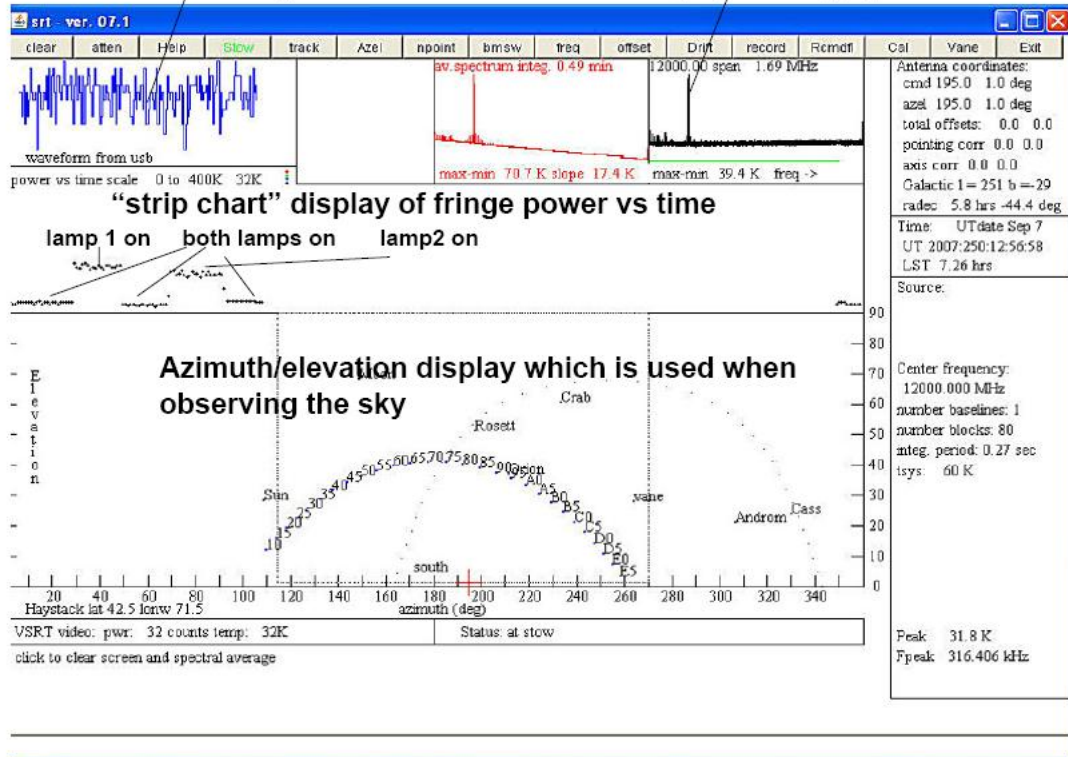


Figure 20 Block diagram of nulling complex source experiment.

waveform from frame grabber

real time display of fringe power



Capture of java screen showing the fringe power which goes down with both lamps on since the set-up is close to the first null in the visibility for a double source.

Figure 21. Example data frames of Experiment 9 (see text).



## Antenna Mounts and Tracking

*Mounts take many forms. The most important criterion for these exercises is that your mounting arrangement be mechanically stable and reproducible.*

### Criteria for simple mounts

The simplest antenna that you have used thus far is the LNB itself. It has a very broad acceptance angle and is easily clamped into position or positioned on a table. Similarly, a Ku-band dish with mounted LNB may be easily mounted on a pole or clamped into position.

Two such dishes may be mounted on a single structure for interferometry studies. The most important mounting criterion is that the mount should be stable. The criterion to pursue in these experiments is that your configuration must be reproducible. You must document your experiments as explained in the Introduction and include sketches and data. You will have already explored different mounting options and should summarize these as sketches in your laboratory notebook.

### Steerable mounts – exercise

In this experiment, you will set up and control a complex steerable mount. Steerable mounts normally are mounted with orthogonal axes for simplicity of control. If motors are used, then the motions are orthogonal. Two common standards are Right Ascension/Declination and Altitude/Azimuth. We will here consider the latter. Two controllable motors may be mounted as shown: in Figure 22

A practicable example of this arrangement is shown in Figure 23.

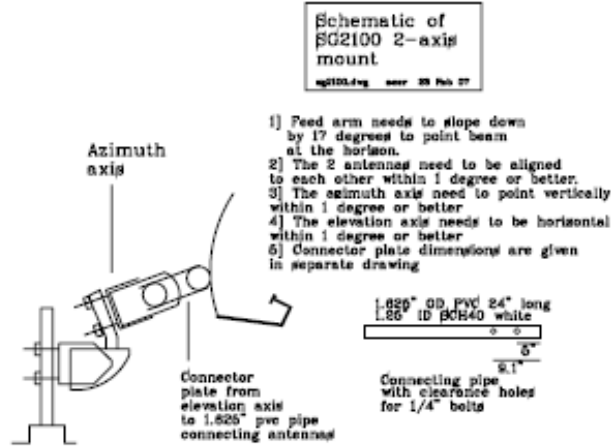


Figure 22. Schematic of two-axis (Altitude/Azimuth) mount.

This configuration can easily drive one 18" dish, and can almost drive 2 such dishes, as shown here:



Figure 23 Example mount configuration. Note the use of a sturdy base tie point.

Unfortunately two dishes strain the motors chosen and it is necessary to add counterweights as shown here. Each counterweight is 2 Kg of lead as shown in Figure 24.

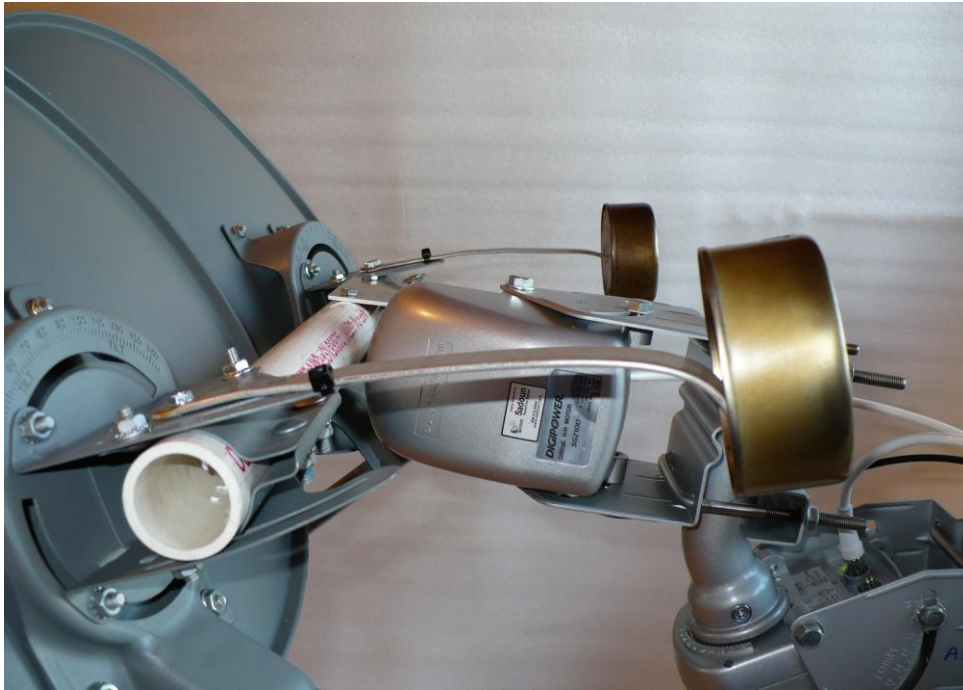


Figure 24. The use of steel dishes results in lower cost, but the small motors are stressed. Lead counterweights of 2 kg mass each and about 20 cm offset are useful.

The two motors, two dishes, two counterweights, LNBS and associated hardware, are a considerable load, so good design practice suggests mounting everything on a rigid pole. Another suggestion is to use aluminum, rather than PVC, for the short horizontal arm shown above. It would also be desirable to vary the separation between the dishes, so the horizontal pipe must be longer than shown.

The unit must be inspected to ensure that components do not touch or bind.

## Tracking

An industry standard communication protocol known as DiSeqc has been developed for simple Staub drives. These motors do well with a single motor controlling a single dish. A single motor in Altitude control operation lifting two dishes is stressed. Thus the aforementioned lead weights may be used. An RS232 solid state switch module may be used to “push” the buttons on a handheld Stab MP01 DiSeqc 1.2 control..

The MP01 generates 3 DiSeqc 1.2 commands:

- 1] Move 1 step East
- 2] Move 1 step West

3] Go to zero position

The buttons can be “pushed” remotely by removing the module cover, drilling an access hole, and soldering wires to the switches. These wires are then connected to the RS232 switch as shown in the block diagram of Figure 25. At least 2 HH90s can be controlled in parallel. The SRT Java software will control the DiSeqc drives and USB video frame grabber. This way the same Java package will be able to support the VSRT interferometer.

The hardware configuration is shown in Figure 25.

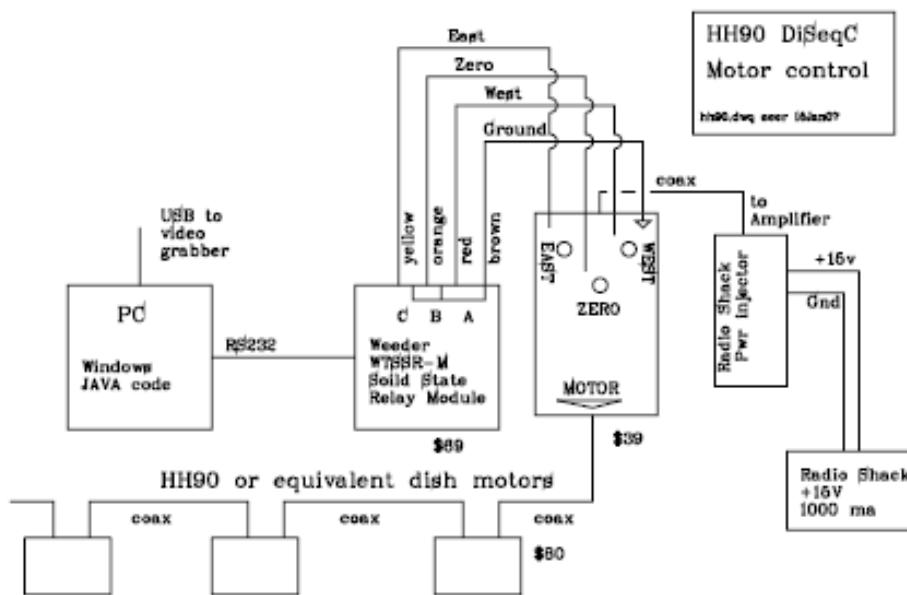
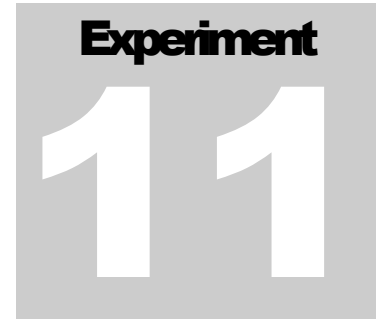


Figure 25 Motor Control electronics driven from the PC serial port.

## Student exercise – pointing

Set up a dual motor system and single dish. Experiment with your Java program changing the srt.cat file to acquire selected sources. Demonstrate acquisition of satellites. Demonstrate acquisition of the sun, and tracking of the sun. Clearly document your work, showing diagrams and photographs when necessary.



## Initial investigations of a celestial source

*To effectively study the sun, it is helpful to track it, thus providing time for averaging the signal and studying transient phenomena. If one has available the VSRT tracking hardware, it may be employed to acquire, track and examine various sources. Temperature may be determined by an absolute measurement.*

### Acquiring the sun with a dish or interferometer

A single Ku band dish may be used to examine the sun. For more extended studies, a tracking system can be built using a “horizon to horizon” satellite dish drive.

Two such dishes may be mounted on a single structure for interferometry studies. The signals from the pair of dishes are added and the fringes extracted using the VSRT em2820-based video grabber. The processing is supported by the Java code and is selected in the srt.cat file using keyword VSRT. With the 2-axis mount the Sun can be scanned using the “npoint” command.

### Absolute temperature determination

With the VSRT setup in interferometer mode, the system responds only to correlated noise so that pointing the pair at a nearby extended object like the ground or trees will produce little, if any, correlated output. Pointing the antenna at an object of brightness temperature  $T_B$  and angular size  $\theta$  will produce an output in each antenna of



$$T_A = \frac{\eta T \theta^2 \pi A}{4 \lambda^2}$$

where T = object temperature

$\eta$  = aperture efficiency

$\theta$  = angular diameter of object

A = geometric area of antenna

$\lambda$  = wavelength

TA = antenna temperature of each antenna

If we use the relation between aperture and beam size then

where  $\theta_b$  = antenna beam full width.

$$T_A = T \left( \frac{\theta}{\theta_b} \right)^2 \left( \frac{(1.22)^2 \pi^2}{16} \right)$$

## Measurement of absolute absorber temperature

Use the VSRT to ensure the temperature of a suspended absorber using the above considerations. What are the sources of error? Estimate the accuracy of your measurement. Remember to subtract the temperature contribution of the atmosphere (about 8K) and that of the receiver (perhaps 60K)

## Measurement of absolute solar temperature

Use the VSRT to ensure the temperature of the sun using the above considerations. What are the sources of error? Estimate the accuracy of your measurement.

## References

Kandu, M.R. (1965), Solar Radio Astronomy. Interscience Publishers, New York .

Kandu, M.R. (1980), in "Radio Physics of the Sun", Proceedings of the Symposium, College Park, MD, August 7-10. Dordrecht, D. Reidel Publ. Co 158-169.

Nita, G.M., D. Gary and L. Lanzerotti, (2004) Space Weather Journal 2 S11005.

## Sensitivity

*Sensitivity determines what sources may be profitably examined. A single-dish and VSRT interferometer will be considered.*

### Importance of sensitivity considerations

The Ku band antenna downconverter feeds (LNBs) are typically illuminated by 45 cm diameter offset parabolic dishes. If the LNBs has a 60 K system temperature and 50% aperture efficiency, the Sun at 12 GHz ( $\sim 4 \times 10^{26}$  J) should provide a signal approximately triple the noise power.

It is useful to calculate the background noise power and relate this to a minimum detectable signal, in order to see what sources might successfully be investigated.

The first sensitivity-related exercise for a student should be to make high sensitivity “single dish” measurements by connecting a single LNB to the set-up shown in Figure 26. Sensitivity for single dish measurements may be increased by a factor of two by removing the splitter from the circuit, if this is a x2 splitter, since with the splitter, the power will be down by a factor of 2. This is a useful trick for determining a 3 dB power reference point for beam width measurements

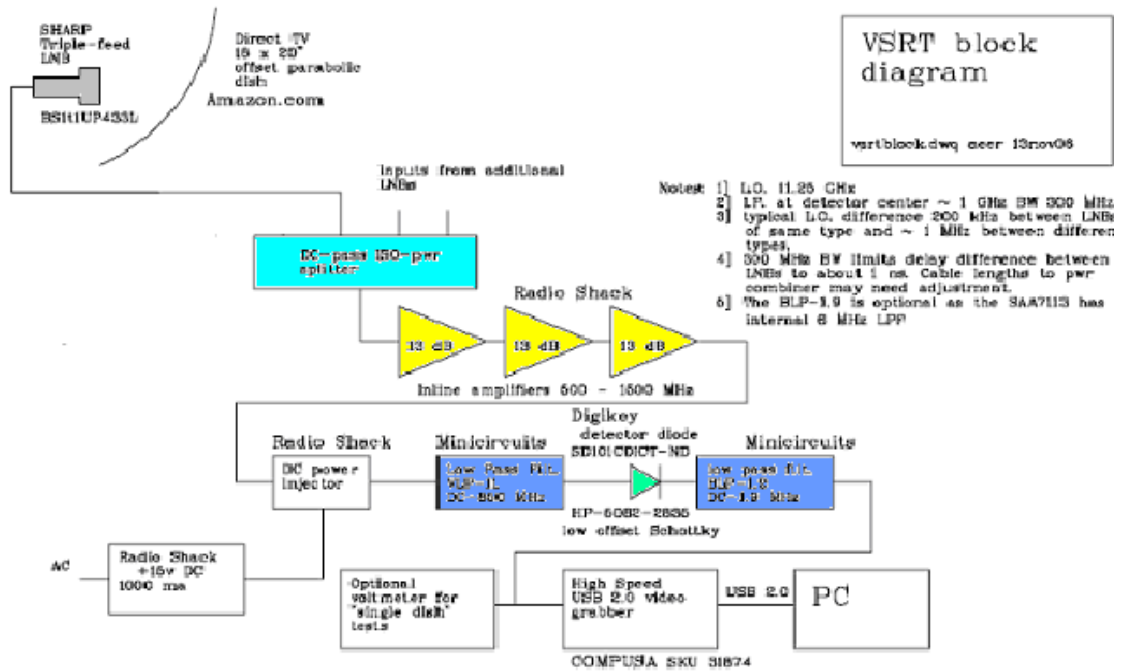


Figure 26. Basic high-sensitivity VSRT block diagram, modified to present experiments for a single dish. The number and type of inline amplifiers (shown in yellow) should be chosen to give adequate gain, below the threshold for oscillation. The splitter (light blue) may be inserted and removed to provide a 3 dB attenuation. The diode represents the envelope detector circuit.

## Multi-antenna sensitivity

With the simple addition of another LNB we have the set-up for a “single baseline” intensity interferometer – the full VSRT interferometer. With uncorrelated local oscillators and a single baseline (two antennas) only the magnitude of the visibility function or “fringe amplitude” can be measured as it is not possible to separate the fringe phase from the local “free running” oscillator phase.

Source strength for detectability

The sensitivity of a radio receiver is determined by the noise:

$$\Delta T = K \frac{T_{sys}}{\sqrt{t\Delta\nu}},$$

where  $\Delta T$  is the root mean square (rms) noise in the output,  $T_{sys}$  is the system noise temperature,  $t$  is the integration time and  $\Delta\nu$  is the noise bandwidth. The constant  $K$  depends on the receiver type. For an interferometer with  $N > 1$  elements,  $K$  will be

$$1/\sqrt{N(N-1)}$$

So for a 2-element interferometer,  $K$  is

$$1/\sqrt{2}$$

For the SRT, the measured antenna temperature (in Kelvin) can be converted to flux in Janskys, where one Jansky is defined as

$10^{-26}$  watts  $m^{-2}$   $Hz^{-1}$ , by the equation

$$S = \frac{2kT}{A_e}$$

Here,  $k$  is Boltzmann's constant and  $A_e$  is the effective antenna area. The Ku band VSRT dishes have a diameter of 0.45 m and an aperture efficiency of 50%. So  $A_e$  is  $(\pi r^2 \eta_{eff})$ , where  $r$  is the antenna radius and  $\eta_{eff}$  is the aperture efficiency. So:

$$S = (T/3.2) \times 10^5 \text{ Jy}$$

## Example calculation of detectability

In order to estimate the probability of detecting a source with a known flux with the VSRT interferometer, we calculate the Signal to Noise Ratio (SNR). If the SNR is greater than about 10, we can expect a good detection.

The SNR is given by the ratio of the observed antenna temperature to the rms noise  $\Delta T$  so that.

$$SNR = \frac{T\sqrt{t\Delta\nu}}{KT_{sys}},$$

or

$$SNR = \frac{0.32 \times 10^{-4} S \sqrt{t\Delta\nu}}{KT_{sys}}$$

So, for a 2-element VSRT interferometer with an integration time of 10s, a bandwidth of 4 MHz and a system temperature of 50K, the expected SNR is:

$$SNR = 0.003 \text{ S Jy}^{-1}$$

### Example calculation for a proposed source

For the double-lobe radio source Cygnus A (the two lobes have an angular separation of  $130''$ ), at a frequency of 1420 MHz (and we will tentatively assume a similar flux at the operating frequency of the VSRT), the measured flux is  $\sim 800$  Jy. This would give an SNR of only 2.4 in a 2-element VSRT interferometer.

### Extension of integration time

This is well below our hope for an SNR of 10, but suppose that we increase the increase the integration time to 100s. Then the calculated SNR is 7.6 and the Cygnus feature is worth searching for.



## Solar Studies

*The sun may be examined as to overall flux, polarization, and structure..*

### Suitability of the sun for study

The sun is our nearest star and is a fascinating object for study. The student should acquire the sun and examine solar intensity and stability. This should be compared to satellite signals.

The student should examine how well the sun may be acquired and tracked using the Java software to control the interferometer.. The sun may easily distinguished from nearby satellites since the sun takes only about 5 minutes to move across the 3 degree acceptance cone of the dish.

### Solar flux measurements

The student should already have measured the temperature of the sun in Experiment 10. The following measurements will extend experience acquired in Experiment 10. You must be able to acquire the solar signal, ensure that you are not examining an artificial satellite, and track the sun for the duration of the experiment.

### Solar circular polarization measurements

Solar polarization may be examined. First, the dishes must be characterized according to their sensitivity to polarization by illuminating them individually by RCP and LCP sources using the CFL lamps equipped with coils as shown in Figure 27:



Figure 27. Standard sources of Left and Right Hand Circular Polarized Ku microwaves are used to set LNB reception for the desired signal polarization. Using the cans will cause overheating of the CFLs so experiments must be done quickly.

It is important that the VSRT be operated with both dishes in the same mode. This is done by setting the DC voltage to select the proper polarization. Since the Direct TV assembly is very common, it will be presented as an example (see Figure 28).

Voltage	22 kHz	Left	Center	Right
13	Off	-	-	RCP
13	On	RCP	-	-
18	Off	-	-	LCP
18	On	LCP (1178-1500)	LCP (940-1178)	-

Figure 28. Example of selection of polarization sensitivity. Parameters shown are for the Direct TV feed assembly with 3 Ku band LNBS. It is desirable to select and use a single LNB during this experiment to avoid the need for refocusing.

Naturally occurring signals not associated with magnetic fields are largely unpolarized, but active solar regions are usually circularly polarized. The voltage on



the LNBS should be varied to change the polarization sensitivity. Care must be taken that the voltage change may select operation of different LNBS in multi-head units and that if this happens, refocusing may be necessary.

## **Solar linear polarization measurements**

The LNBS may be made sensitive to linear polarization (detected occasionally on the sun).

A grid of crossed wires may be placed in front of each LNB. The direction of the wires selects the direction of the electromagnetic field vector.

## Solar raster images

The VSRT can be operated in raster scan mode to image celestial sources. Figure 29 shows the results of a VSRT scan of the sun.

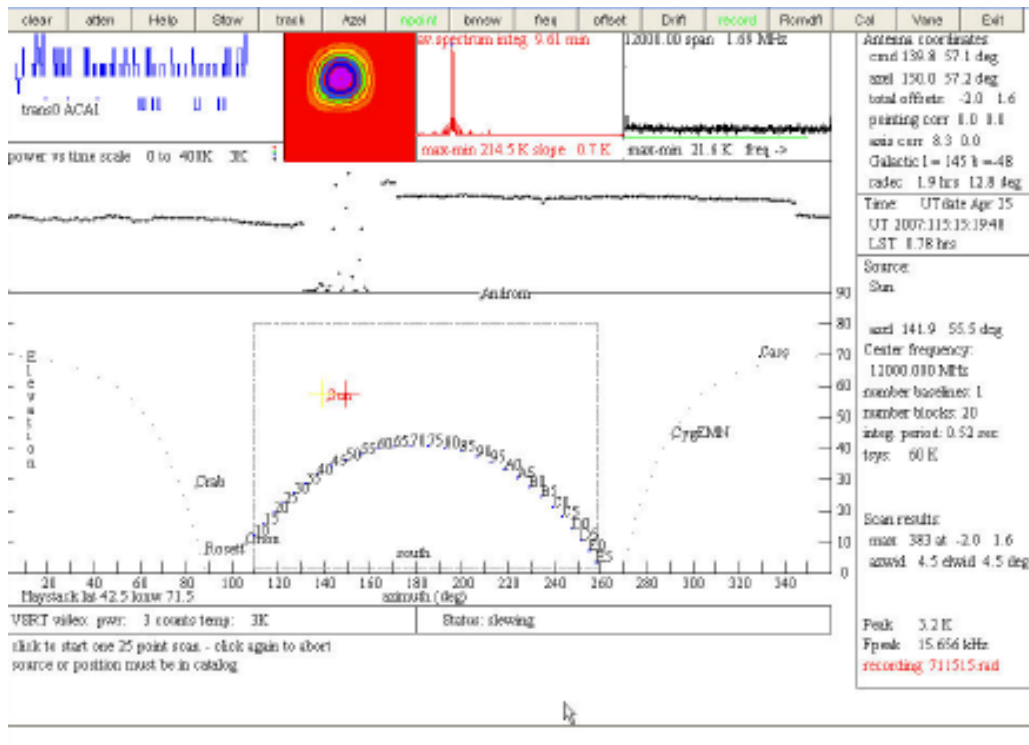


Figure 29. Shown here are the results (in the red scan box) of a 5x5 point raster scan of the sun. It is important to ensure alignment and tracking accuracy before beginning such measurements

## Scanning fixed extended objects

The student should use the VSRT in scan mode to scan a fixed irregular object that subtends at least 2 degrees. A tower or the edge of a building will suffice.

The student should use the VSRT in scan mode to scan a portion of the Clarke belt, showing at least two satellites. Note that the Clarke belt, once acquired, does not require active tracking since the satellites are in synchronous orbit.

## Scanning orbiting celestial objects

The student should use the VSRT to scan the sun.

## **Tropospheric scintillation measurements**

The VSRT will respond to scintillation in the troposphere or in the interstellar medium. Try to detect this short-term scintillation by monitoring the sun.

Scintillation in the troposphere is due to plasma effects and will respond to solar-terrestrial magnetic field coupling and decoupling. Interstellar medium scintillation will be due to modulations of the index refraction due to the solar wind.

## **References**

Kandu, M.R. (1965), *Solar Radio Astronomy*. Interscience Publishers, New York .

Kandu, M.R. (1980), in “Radio Physics of the Sun”, *Proceedings of the Symposium*, College Park, MD, August 7-10. Dordrecht, D. Reidel Publ. Co 158-169.

Nita, G.M., D. Gary and L. Lanzerotti, (2004) *Space Weather Journal* 2 S11005.

## Ku band Satellite Studies

*Satellite signals may be both a source of test and setup signals, and a source of interference.*

### Satellite signals

The VSRT without any filtering accepts signals as defined by LNB characteristics. Thus it accepts signals over a broad band from about 11.5 to 13.2 GHz since the I.F. extends from about 0.3 to 2 GHz. With this wide open bandwidth the Clarke belt signals limit observations of the Sun to within 15 degrees of the Clarke belt or a declination magnitude over 15 degrees. Typical satellite signals have a flux density about equal to the quiet Sun ( $\sim 5 \times 10^{-6} J$ ) but go up to about twice the quiet Sun. Limiting the I.F. to less than 900 MHz, which restricts the band from 11.5 to 12.1 GHz, makes little if any improvement. However, if the I.F. is limited to over 1600 MHz, the satellite signals are eliminated down to the detection threshold of the VSRT.

### Scanning using the VSRT

The student should acquire and track several satellite signals. Examine their distribution across the sky, stability of their signal, and the ability of the system to acquire the signals by selecting sources on the VSRT Java program.

### Clarke belt structure

The student should use the VSRT in scan mode to scan a portion of the Clarke belt, showing at least two satellites. Reasons for the location and satellite spacing should be discussed in your lab book. When weak signal sources (satellites) are noted, reasons for their low signal should be discussed.

### Satellite circular polarization measurements

Satellite polarization should be examined. The polarization will usually be circularly polarized. The DC power voltage on the LNBS should be varied to change the

polarization sensitivity. Care must be taken that the voltage change may select a different LNB on the multi-LNB receiver units and refocusing may be necessary.

Polarizations found should be noted and the reasons for the pattern of detected polarization discussed.

## **Tropospheric scintillation measurements**

The VSRT will respond to scintillation in the troposphere. Try to detect this short-term scintillation by monitoring selected satellites. Satellites at higher elevation angles should give cleaner data.

Scintillation in the troposphere is due to plasma effects and will respond to solar-terrestrial magnetic field coupling and decoupling.

## Phase Closure

*A closure phase may be computed for 3 or more detectors and shown to be 0 or 180 degrees. Its actual value is sensitive to the symmetry of the source. This technique can be developed to make sensitive and sophisticated measurements.*

With 3 (or more) LNBS the phase of the fringes can be related by summing them around a triangle of baselines. In this case, we get a “closure” phase for which the local oscillator phases cancel when the LNBS are looking at the same source. In this case, there will be three detected signals,  $f_0$ ,  $f_1$  and  $f_2$ , corresponding to the frequency differences between the LNBS, taken in pairs.

The phases can be determined by computing

$$\phi_y = \alpha \tan 2(-\text{Im}, \text{Re})$$

where Re and Im are the real and imaginary components of the FFT at the frequency for which the fringes appear for this baseline. The closure phase is given by

$$\phi_c = \phi_{01} + \phi_{12} - \phi_{02}$$

and phase closure is a statement that

There is a sign ambiguity in the determination of the fringe phase from atan2 above. This

$$\phi_{01} + \phi_{12} - \phi_{02} = 0 \text{ or } 180 \text{ degrees}$$

is because we only know the magnitude of the difference of local oscillator (L.O.) phases.

Equivalently, we may express the closure phase relation by requiring the frequencies of the local oscillators to obey the analogous relation,

$$f_0 + f_1 - f_2 = 0$$

where  $f_0$ ,  $f_1$  and  $f_2$  are the local oscillator frequencies in increasing order.

### Student validation of phase closure

The student should set up an apparatus consisting of three LNBS or three dishes with LNBS (depending on whether the experiment will be performed inside or outside, for better signal to noise ratio and lower background), as shown in Figure 30.

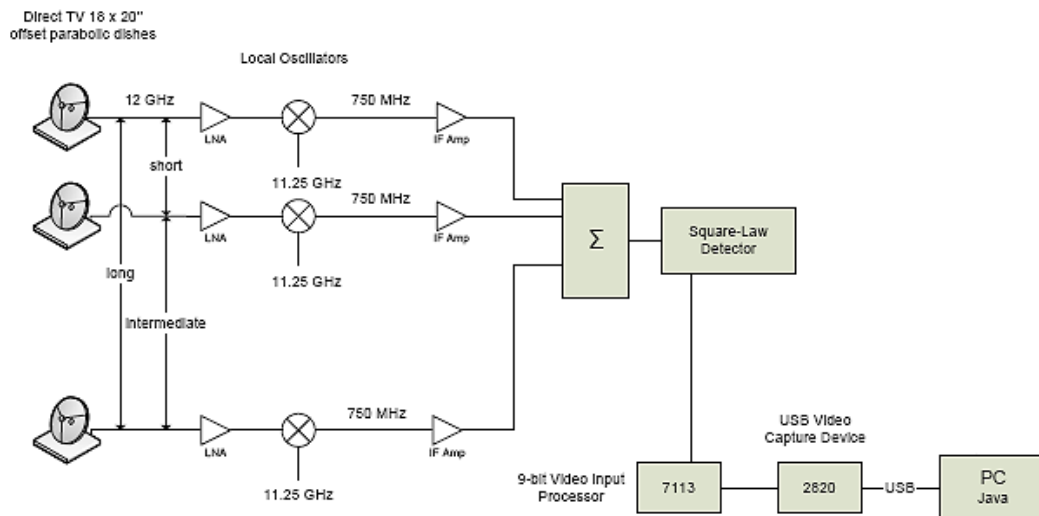


Figure 30. Block diagram of 3-detector VSRT.

The SRT software (in VSRT mode) can analyze the fringe phase from 3 baselines to form the closure phase. The student should connect 3 LNBS to the splitter. With a single source, the frequency statement of the closure phase should be measured and shown to be zero within the noise. Note that the LNBS undergo a period of instability but become fairly stable in less than a minute provided that the temperature does not drift.

## **Student demonstration of phase closure failure**

The student should also show that phase closure does not occur if two lamps are used to produce an asymmetric double source.





## Corrections, Addenda, and Notes

*Students are invited to record their comments on this page and to send them to the authors for consideration in future experiment manuals. Notations of errors and suggestions for improvements will be greatly appreciated.*

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