The hardware and software configuration of a typical SUG station is described below and help define a SUG station’s baseline capability. This report is an extension and update of several previous documents.¹,²,³,⁴

A station’s reception capabilities may be characterized in terms of its hardware, software, and observing conditions. These components control station sensitivity and the resulting data’s accuracy in time, amplitude, and radio frequency.

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The configuration of a baseline SUG station is shown in Figure 1 below.

Figure 1 – The baseline SUG station hardware and software configuration.
Abbreviations

dBi – Decibels relative to an isotropic radiator
FSX – Flagg Sky Spectrograph
FFT – Fast Fourier Transform
GB – Galactic Background
HEC – Heliophysics Education Consortium (now NSSEC)
LAN – Local Area Network
LCP – Left Circular Polarization
NTP – Network Time Protocol
NSSEC – NASA Space Science Education Consortium
PC – Personal Computer
RCP – Right Circular Polarization
RJP – Radio Jupiter Pro
RSP – Radio Sky Pipe
RSS – Radio Sky Spectrograph
SDR – Software Defined Receiver
SUG – Spectrograph Users Group
TFD – Terminated Folded Dipole

1 – TFD Array and Feed System

The baseline SUG station antenna as shown in Figure 2 comprises four TFD (terminated folded dipole) elements arranged in a square array connected through a hybrid ring to produce right and left hand circular polarization outputs simultaneously.5

Figure 2 – The 4-element 24’ TFD array installed at Heliotown (Lamy, NM). Photo by Tom Ashcraft.
1.1 – TFD Array

The standard array with 24 ft long elements is useful over at least the 15 to 30 MHz slice of the RF spectrum. The array includes the ability to steer the antenna beam in the NS direction using manually inserted time delay cables.

Specifications of the array vary with frequency; but, at 20 MHz the array has a directivity of 11 dBi (for unpolarized emission), a gain of 6.7 dBi, and a half-power beam width (HPBW) of approximately 45° when steered to the zenith. Internal losses in each TFD element of 4.3 dB at 20 MHz account for the difference between directivity and gain and cause the typical 20 MHz GB temperature at the antenna terminals to be 19 kK (vs 50kK with a 20 MHz half-wave dipole antenna which is nearly 100% efficient). Directivity, gain, beam width, and polarization crosstalk vary with frequency and beam steering angle.

A detailed analysis of the polarization characteristics has not been made although it has been noted that an 8-element TFD Array (AJ4CO) may show unpredicted polarization responses when exceeding 45° off-axis operation.

1.2 – Feed System

Low loss coaxial cables (one for each polarization) transfer the received signals from the array to the receiver’s location. In most cases the cables carry orthogonal linear signals from the antenna to surge suppressors tied to an earth ground, then to an amplitude calibrator, then to the polarization hybrid located near the receivers. In other installations the hybrid is located at the antenna and the cables carry orthogonal circular signals. Locating the hybrid outdoors at the antenna array is not recommended because the hybrid may be damaged by the surge voltage induced by nearby lightning strikes. Losses between the antenna and receiver interface are on the order of 3 dB. These losses further reduce the 20 MHz galactic background signal to about 10kK.
1.3 – Terminated Folded Dipole (TFD) Array Summary

Element Length: 24’
Number of Elements: 4
Element Configuration: square array, 26’ on each side
Bandwidth: 15-30 MHz
Zenith Directivity @ 20 MHz: 11 dBi assuming unpolarized emission
Zenith Gain @ 20 MHz: 6.7 dBi assuming unpolarized emission
Zenith Beamwidth @ 20 MHz: 45 deg, steerable
Polarization: simultaneous LCP and RCP

2 – Amplitude Calibration System

Development of a 15 to 30 MHz automatic calibrator was funded in 2016 by HEC before HEC was renamed NSSEC. Thus the instrument, formally named the FBS100, became known as the HEC calibrator, an example of which is shown in Figure 3.6

![Figure 3 – The HEC-funded amplitude calibrator.](image)

Half a dozen units were manufactured and distributed to SUG stations (Ashcraft, Brown, Higgins, Greenman, Reyes, Mount).

The HEC calibrator hardware comprises an Arduino Uno, a GPS receiver and antenna, and a hot noise source. It can calibrate simultaneously both RCP and LCP channels of a spectrograph system using the dual polarized TFD antenna.
and the FSX polarization switching spectrograph. Using GPS timing as a trigger, the unit will sequence thru a range of noise temperatures in 3dB steps.

A front panel LCD display shows the GPS derived Universal time and the actual output temperature during calibration sequences. The operator can select fast (5 second) or slow (10 second) dwell times during the calibration run and also control the calibration range with toggle switches (for Jupiter max temp = 800kK, for Sun max temp = 100 MK).

The HEC calibrator proved to be overly complex to fabricate in terms of unit cost and it only produced a stair-step of temperatures visible in RSS or SkyPipe. The toggle switches were seldom used and the LCD display added little functionality. Only through an arduous manual process could one match calibration colors on the RSS display with observed emission burst colors to estimate antenna temperatures.

In order to achieve a more useful calibrator, the Mark 2 (MK2) is currently being developed (May 2019). This unit is controlled via a USB connection to the RSS computer. The calibration sequence is triggered by RSS using the computer’s clock. Numerical values of each calibration temperature are transmitted from the MK2 to the computer. This data allows RSS to calculate and display the antenna temperatures of pixels within the RSS spectral display.

In addition, RSS will use the calibration temperatures to plot response curves for the spectrograph being controlled by RSS. This allows the operators of SDRs to view the results of adjusting software controls to optimize sensitivity and dynamic range.

The existing HEC calibrators will be updated to MK2 functionality by uploading new Arduino code. MK2 calibrators will be fabricated for use at future SUG spectrograph stations.
3 – Multicouplers (MCs)

Two 4-port multicouplers allow for the distribution of both LCP and RCP signals to the spectrograph and other receivers which may be in use (such as a Jove receiver). The multicouplers, an example of which is shown in Figure 4, include bandpass filters which pass at least the 15-30 MHz frequency range. The gain of the MC is typically 10 dB for port 1, and 3 dB for ports 2, 3, and 4.7

![Multicoupler](image.png)

Figure 4 – A typical multicoupler used by SUG stations.

4 – Timing Calibration System

The data recorded by RSS and RSP rely on the PCs’ system clocks to generate time stamps. For single-frequency strip chart data, each data point recorded by RSP is time stamped. For spectral data, however, individual frequency sweeps or FFT output blocks recorded by RSS are not time stamped. Rather, only the first and last sweep or FFT block within the spectral data file is time stamped. When reviewing the data later, the times of the sweeps between are interpolated by RSS. When spectral data is served over the internet to a remote RSS client, the client computer assigns the client PC clock’s time to the received spectrogram image. Thus, Internet latency and client computer clock errors can result in a shift of the resulting spectrogram’s time axis when viewed on a client machine.
4.1 – Gps-Ntp-Pi Hardware

Each PC recording and serving data has the capability to use an NTP client program to poll a GPS-based NTP server. The NTP server in use is shown in Figure 5, the Gps-Ntp-Pi from Whit Reeve. This unit provides NTP to any device on the LAN to which it is connected.

![Figure 5 – The Gps-Ntp-Pi NTP server and external GPS antenna.](image)

4.2 – NTP Client Software

The NTP Client software in use is the Meinberg NTP Client and the Meinberg NTP Time Server Monitor; both are freeware. The Atomic Clock function within RSP may also be used in lieu of the Meinberg software, but sacrifices user control over how often the PC’s clock is updated and does not provide the same degree of logging ability.

This GPS-based time calibration system is thought to keep PC clocks to within a few milliseconds of UTC; however, rigorous testing has not been performed. The Gps-Ntp-Pi time server itself has a stability (Allan deviation) of 1.0 to 1.5 μs.
5 – Receivers and Data Recorder Systems

5.1 – FSX Spectrograph

5.1.1 – FSX Spectrograph Hardware

The SUG station primary instrument is the polarization switching FSX Spectrograph (Figure 6). In the polarization switching mode the FSX monitors one polarization input for 150 ms as it sweeps through 300 channels and then switches to the opposite polarization input for the next 150 ms.

Figure 6 – The FSX polarization switching spectrograph.

5.1.1.1 – Sweep Rate and Dwell Time

The FSX machine steps thru 2000 channels (frequencies) every second, measures the intensity of the signal at each frequency, and sends that data to Radio Sky Spectrograph (RSS) software that saves the data to disk and provides a displayed spectrogram. The dwell time at each frequency is 500 μs.
5.1.1.2 – Frequency Range and Bandwidth

The width of each channel as determined by the pre-detection bandwidth of the FSX is 30 kHz. For typical operation the FSX is configured for 300 channels, each channel 30 kHz wide, spaced every 50 kHz from 15 to 30 MHz. The center frequency of each channel is determined by a crystal controlled oscillator and is likely within a few kilohertz of the calculated value. Exact measurements of frequency accuracy have not been made. In the typical configuration of 300 channels and the sample rate of 2000 channels per second, a single sweep takes 150 ms, producing spectral data at a rate of 6.7 sweeps per second.

5.1.1.3 – Noise Figure

The FSX itself (operated without a multicoupler) has a noise figure of about 7 dB meaning it would add about 1,100 kelvin to the approximately 10,000 kelvin temperature delivered by the TFD array due to the galactic background. Therefore the noise contribution of the receiving system itself is insignificant compared to the galactic background noise level. The multicoupler will further reduce this already negligible noise contribution.

5.1.1.4 – Dynamic Range

The FSX uses a 12 bit analog to digital converter and has a dynamic range of 40 dB above the galactic background meaning that it can accommodate a radio noise burst of 100 million kelvin without saturating. Jupiter bursts with the TFD antenna are seldom stronger than 15 to 20 dB above the background and very strong solar bursts may reach several tens of megakelvin (~30 dB above background).
5.1.1.5 – Minimum Detectable Signal

The minimum detectable signal (temperature) of the FSX is determined by the magnitude of the statistical fluctuations of the background noise (primarily the galactic background).

\[
\Delta T_{\text{min}} = \frac{n \sigma T_{\text{sys}}}{\sqrt{B \tau}} = \frac{3(50,000 \text{ K})}{\sqrt{(30,000 \text{ Hz})(0.0005 \text{ s})}} \approx 40 \text{ kK}
\]

\(\Delta T_{\text{min}}\) = Minimum detectable noise temperature fluctuation
\(n\) = number of std dev required for valid "detection" of a signal (in this case 3)
\(T_{\text{sys}}\) = galactic background and receiving system noise
\(B\) = the pre-detection bandwidth of the receiver
\(\tau\) = the post-detection integration time constant

The main parameter limiting sensitivity is the short integration time of 500 μs. This value was chosen so that the FSX would have a reasonably good time resolution (time between sweeps = 150 ms) while achieving a frequency resolution of better than 50 kHz while sweeping over a 15 MHz range.

5.1.1.6 – FSX Spectrograph Summary

Frequency Range 15-30 MHz
Noise Figure: 7 dB
Pre-Detection Bandwidth: 30 kHz
Sweep Rate: 2000 channels per second
Integration Time: 500 microseconds
ADC: 12 Bit
Dynamic Range: 40 dB (10kK to 100MK)

5.1.2 – FSX Spectrograph Software

The RSS software takes data from the FSX, displays it, can make it available for remote clients in near real time, and stores it for later review. Since the polarization switching FSX monitors two polarizations, RSS displays these two polarizations on two panels – with RCP on the top panel and LCP on the bottom panel (Figure 7).
Figure 7 – Polarization switching spectrogram taken by Greenman during an Io-C storm. RCP top panel, LCP bottom panel.

5.1.3 – FSX Spectrogram Examples

FSX series spectrographs, in operation since 2008 have a rich historical record comprising thousands of spectrograms. Polarization switching capability was added in 2015. Instrument parameters were optimized for reception of Jovian L-burst emission while allowing identification of S-burst activity. These spectrographs have proven suitable for observations of the galactic background, Jupiter, the Sun, Cas A scintillation, and various ionospheric phenomena. See Figures 8 through 12.
Figure 8 – The diffuse galactic center (0400-1400) is seen on this 24 hour spectrogram as well as terrestrial stations (horizontal lines), and faint sloping features (from 1700-0200) called propagation TPs.

Figure 9 – Jupiter Io-B emission from AJ4CO (8 element TFD array).
Figure 10 – Solar burst followed by a radio blackout observed in Hawaii at WCCRO. Notice numerous stations prior to the solar burst which then disappear. The blackout is caused by solar X-ray flux causing heavy ionization and absorption of HF signals in the Earth’s ionospheric D layer.

Figure 11 – Faint whispy enhancements of signals from Cassiopia A.
Figure 12 – Propagation TPs with enhancement of CB band reception at 27 MHz.
In recent years, software defined radios (SDR) of modest bandwidth capability (producing spectra 8 MHz wide, versus 15 MHz wide for the FSX) have become available at low prices (under $200 each) as compared to the polarization-switching FSX ($1,400). SDR receivers typically operate over a wide tuning range extending from well below 10 MHz to 1700 MHz or above. Such SDRs as the Airspy, KiwiSDR, and SDRPlay (RSP1, RSP1A, RSP2, and RSP2Pro) are currently being evaluated to determine their suitability for Jupiter and Solar observations.

Low bandwidth units such as the Funcube Dongle Pro (192 kHz bandwidth) and a host of RTL dongles (2.3 MHz bandwidth) are also available. Some SDR’s can be operated with RadioSky Spectrograph (RSS) software; the most promising units as of this writing are made by SDRPlay.\textsuperscript{12}

SDRPlay first produced the RSP1, then the RSP2, and more recently the RSP1A and the RSP2Pro – see Figure 13. The 1A has a 14 bit ADC and the RSP2 has a 12 bit ADC. They can be operated as “traditional” radios by using SDRUno software. This software can be used to tune an RSP unit center frequency and demodulate a wide variety of signal types. The SDRUno display also provides a calibrated signal strength monitor.

Figure 13 – SDRPlay RSP2Pro (left) and SDRPlay RSP1A (right).
5.2.1.1 – SDRPlay Sensitivity

SDR spectral displays are generated via fast Fourier transform (FFT) which can provide longer integration times than the FSX and hence improved sensitivity. For example when we use a 0.1 second integration time with the SDRPlay, the sensitivity of the SDRPlay is improved over the FSX by:

\[ 10 \log (\sqrt{\frac{FSX}{SDR}}) = 10 \log (\sqrt{0.1/0.0005}) = 10 \log(14) = 11 \text{dB} \]

5.2.1.2 – SDRPlay RSP2 Antenna Switch

The RSP2 is capable of switching between three antennas. One is a high impedance input suitable for a long wire. The two SMA ports are for 50 ohm antennas. Nathan Towne has implemented the ability to switch rapidly between the two 50 ohm antenna ports in order to replicate the capability of the polarization switching FSX machine. Unfortunately switching transients and possible cross talk between channels continue to be issues. It was hoped that a single RSP2 could provide dual polarization spectrograms covering 8 to 10 MHz of the RF spectrum (e.g., 18 to 26 MHz), but so far that goal has not been achieved.

As of this writing, the SDR testing participants have determined that polarization switching on the SDRPlay RSP2 or RSP2Pro simply will not work for radio astronomy. If two simultaneous polarizations are to be recorded, two RSP2 or RSP2Pro units and two PCs will need to be employed.

5.2.1.3 – Overload

With very careful setting of the RSP controls it is possible to achieve a dynamic range in excess of 30 dB. However, the units are quite susceptible to overload by strong in- and out-of-band signals. Various filtering experiments have been tried in order to minimize overload. This issue has not been completely resolved. An example of the spectral signature of overload is shown in Figure 14.
Figure 14 – Overload is manifest by signal leakage into adjacent FFT bins. Here we see overloading caused by international broadcast stations in the 17-18 MHz frequency range and also at 21.5 MHz.

5.2.1.4 – Computers

Since the RSP units rely on software FFT solutions performed in the host PC, the processing capability of the PC becomes important. Jim Brown, Larry Dodd, and others have experimented with several different computers with mixed results. In very general terms, legacy laptops appear to be problematic. Desktop units with processors such as i3, i5, and i7 types have been tried. The results ranged from marginal using an i3 to excellent using an i7. Processor utilization under 15% is typical of the i7 CPUs whereas a Minix Z83-Pro with an Atom XX5-Z8350 CPU running at 1.44 GHz pegged at 100% utilization trying to run an RSP2 at modest bandwidths. The characterization of a PC’s processing power is not trivial. Although various benchmark tests are available, it is unclear whether these tests replicate the computational load of an RSP unit. Raw CPU speed, the number of cores, the amount of available memory – all of these factors and more are important.

5.2.2 – SDR Spectrograph Software

Jim Sky of Radio Sky Publishing has written the RSS spectrograph software used with the FSX and RSP spectrographs. Nathan Towne has written the control and interface software used with the RSP instruments. Both software developers are independent and occupied with many projects. There is currently no funding for
software upgrades and bug fixes. The acquisition and analysis of spectrograph
data is critically dependent on continued software development and refinement.

Nathan Towne has written a control and interface program called SDRPlay2RSS
which allows control of an SDRPlay receiver and acts as a bridge between the
SDRPlay hardware and RSS.\textsuperscript{13} In this way RSS can be used for spectrogram
display and data acquisition in the same way it is used for the FSX spectrograph.
The user interface of the SDRPlay2RSS software is shown in Figure 15.

![SDRPlay2RSS Interface](image)

Figure 15 – The operation of the SDRPlay is clearly much more complex than the
FSX machine, which simply has an ON/OFF toggle switch. All of the SDRPlay
controls must be carefully set to achieve a useful sensitivity and dynamic range.

5.2.3 – SDR Spectrogram Examples

Jim Brown of HNRAO has done the bulk of on-the-air testing of the SDRPlay
units. Wes Greenman of Radio Alachua and Larry Dodd are also operating
SDRPlay units. One SDRPlay is in service at WCCRO in Hawaii. Several
SDRPlay generated spectra revealing excellent detail in both Jovian and Solar
bursts are shown in Figures 16 through 18.
Figure 16 – A Jovian N-event.

Figure 17 – Modulation lanes are seen in Jovian L-bursts.
5.3 – JOVE Receivers

Since SUG is an outgrowth of the Radio JOVE program, most SUG observers run JOVE receivers in addition to spectrographs. These single-frequency receivers operate at 20.1 MHz ±200 kHz, their data being recorded on a host PC by RSP. The JOVE receivers are connected to the RCP and LCP multicouplers. Amplitude calibration is achieved in the standard way for a JOVE receiver, but using the HEC calibrator in lieu of the RF-2080 C/F noise source.

6 – Station Operations

Factors affecting station operations include the prevailing observation conditions (presence or lack of RFI), inclement weather (lightning, hurricanes), reliability of electrical service, reliability of computer hardware and software, and availability of staff to monitor the instruments and keep everything running smoothly. Stations with access to the internet may set up RSS to serve data to other observers who use the remote client feature within RSS.

6.1 – Station Availability

SUG station operation schedules range from 24x7x365 to sporadic to not-yet-operational.
6.2 – Beam Steering

SUG stations steer their antennas to put the beam centerline on Jupiter transit. During the Jupiter observing season, roughly 7 months per year, this limits the stations’ availability for observing other phenomena.

6.3 – SUG Station Clusters

The performance characteristics of a cluster of stations remains speculative as no efforts to combine data from multiple stations have yet been made by any researchers. Furthermore, the overall data handling and archiving process involving multiple stations operating in a cluster is unknown and no signal analysis methodology or software has been identified, characterized, or developed. Solutions to these outstanding issues should be developed during operation of a prototype cluster.

7 – Data Storage and Availability

Most SUG stations record spectral data to their own hard drives or to HEC-funded 1 TB portable hard drives. RSS records spectral data in a proprietary albeit publicly-documented “SPS” file format. For dissemination, data is transferred in bulk to portable hard drives, one at each SUG station, and sent on a poorly-defined schedule (around once per quarter to once per year) to the Planetary Data System (PDS) at UCLA for storage and conversion to CDF file format. The PDS also provides public access to the native SPS files. Thus, there is presently no way for SUG stations to easily share spectra data files in a timely fashion. The SPS data files range in size from 320 to 640 MB per day of observation for each receiver at each station. SUG stations run between one and five spectrographs, thus the volume of data generated each day by one station can be several gigabytes.

Acknowledgement

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References