# Laboratory for Radio Science Instrumentation Research at the University of Virginia

## *A Conceptual View*

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## Introduction

This document presents my thoughts on the creation and administration of a new laboratory and graduate education program for radio science instrumentation research. At present, this document summarizes only my personal viewpoint, but through your comments and suggestions it is my hope that together we can mold this introductory material into a workable plan, and by the end of this year, an NSF Integrative Graduate Education and Research Training (IGERT) proposal. In short, it is my personal desire to create a state-of-the-art research laboratory and integrated educational environment that will not only meet our current needs in radio astronomy but will also form a strong foundation that will allow us to expand the focus of the program to meet the needs of the radio science community well into the 21$^{st}$ century.

## Motivation

There is a growing need for a state-of-the-art research laboratory in radio astronomy. Radio astronomy is a science whose progress is driven by the pace of technological improvements to its research instruments. Although the pioneering work in this field was conducted prior to 1940, the infant science did not fully blossom until after World War II. Major advances in the science came in the post-war era, primarily due to the availability of the superb radar instrumentation developed during the war at the MIT Radiation Laboratory, and also because of the interest of brilliant technologists who had excelled as radar and radio engineers when driven by the war effort. It was evident then, and it is ever so clear today, that in order for a radio astronomer to work at the forefront of the discipline, the instruments that are employed must be at the forefronts of the associated technologies.

Through the efforts of our national facilities dedicated to radio astronomy, scientific research in this field over the next decade will be greatly enhanced by the new National Radio Astronomy Observatory's (NRAO) 100 meter Green Bank Telescope (GBT), improvements to the National Astronomy and Ionospheric Center's (NAIC) Arecibo telescope, the international Atacama Large Millimeter Array (ALMA) project, the planned NRAO Very Large Array Upgrade, and the Smithsonian Astrophysical Observatory's (SAO) Submillimeter Array on

Mauna Kea. However, over the long run, the scientific return from such large scale telescopes is compounded only by continued advances in the instrumentation art. It is here where our national facilities are struggling. Over the past several years severe budget constraints have forced these laboratories, once undisputed leaders in instrumentation research, to direct their shrinking resources to address immediate needs, with very little remaining to support long term instrumentation work, i.e. the sustained instrumentation *research* has been replaced by project-oriented, component and system *development*. The strong emphasis on arrays creates an additional problem in that the organizations are thinking more and more about the economic *production* of electronic components rather than new concepts in component research. The time is right to consider moving the *research* aspect of radio astronomy instrumentation to the academic setting. Such research is truly an interdisciplinary art and the academic environment at the University of Virginia is ideal for such a program to flourish.

## Purpose

The purpose of this program is to actively link together the scientists having ideas for instruments that may open new avenues of research, the physicists with new device concepts resulting from their own basic research, and the engineers with experience in associated disciplines to enhance the state-of-the-art of radio science instrumentation. Graduate students from engineering and science will work together on all aspects of the instrument from concept to design, from component fabrication to assembly, evaluation, and calibration. In many cases, the same group will be involved in instrument deployment, data collection, and data analysis. It will be a team effort that fosters interaction between faculty and students across disciplines and departments.

There are plenty of research opportunities in modern radio astronomy instrumentation. Today, improvements are needed in portable site survey instruments such as submillimeter wave tipping radiometers, Fourier transform spectrometers, and RF interference monitors that will yield a more comprehensive evaluation of proposed telescope sites around the world. The telescope itself can be improved by using array feeds that increase the instantaneous field of view, by implementing side-lobe corrections measures, by enhancing antenna pointing accuracy, and by better antenna surface accuracy through real-time correction systems. Radiometers could be improved through larger feed bandwidths, ultra low noise cryogenic amplifiers, novel detectors, and better component dynamic range. Modern digital signal processing techniques could be employed to increase spectrometer bandwidth, study and apply atmospheric and ionospheric phase corrections, implement RF interference countermeasures, and improve SETI search and detection techniques. Therefore, a detailed integration of many technological disciplines including semiconductor device research, submillimeter wave electronics, digital signal processing, communication technologies, photonics, quantum electronics, cryogenics, micro-machining, and others will be required to make significant advancements to the state-of-the-art of research instrumentation.

Although the initial focus will be astronomy it is the long term goal of the new program to provide the framework for the exchange of technology and ideas throughout the many fields of radio science. Radio science covers a wide range of research disciplines including electromagnetic metrology, wave propagation, remote sensing, ionospheric radio propagation, waves in plasmas, electromagnetic interactions in biology, chemistry and medicine as well as radio astronomy. For example, the Laboratory would be suitable for research in ultra-low noise RF amplifiers based on InP HFET and dc-SQUID technologies having noise temperatures under 1 Kelvin to aid studies in condensed-matter physics and enhance ongoing cosmic axion search experiments. Such amplifiers could be integrated with Single Electron Transistors (SETs) forming new photon detectors for astronomy. Modern microwave circuit techniques could be employed to make simultaneous multi-frequency Electron Spin Resonance (ESR) systems to study metal-protein interactions or to improve the signal-to-noise ratio of coupling coils in Magnetic Resonance Imaging (MRI) microscopy for medical applications . Special millimeter wavelength radio polarimeters could be developed for monitoring ocean surface wave motion in real time giving us a better understanding of our global environment. Noise and interference in measurements can be reduced through the application of modern adaptive interference cancellation techniques. All of these research endeavors are closely tied with ideas from the study of radio astronomy instrumentation.

## Laboratory Environment

Central to the program will be the state-of-the-art Radio Science Instrumentation Laboratory located (hopefully) in the basement of the UVa astronomy building. The Laboratory will consist of four domains. The *design and simulation area* will consist of computer workstations and associated peripherals for running the latest design software including HP-ADS, MATLAB, AutoCAD, etc. A *clean micro-assembly area* will include microscopes, fabrication equipment, and assorted hand tools for the assembly of modern components and circuit boards involving very tiny semiconductor devices. The *prototype systems assembly area* will consist of soldering stations, hand tools, and other articles necessary for fitting components into the overall system. Finally, the *testing area* will provide electronic, radio, and microwave equipment for component tests as well as full scale system evaluation. A list of the major equipment and other items for the Laboratory is presented in Appendix A.

Active student participation in all aspects of the research projects is the core feature of the laboratory. However, it also important to provide some long term continuity in the training of these students in accepted laboratory procedures, safe fabrication practices, and practical circuit and mechanical design issues. Such training is most effective in an apprenticeship-type environment. Therefore, the Laboratory will be staffed by a full time electrical engineer and a full time electronics technician to provide the long term continuity within the program.

The vitality of the laboratory research and educational program lies in its synergy with other groups in the UVa School of Arts and Sciences, UVa School of Engineering and Applied Science, the NRAO Headquarters, and the NRAO Central Development Laboratory. Such associations provide access to fabrication equipment not available at the laboratory, ties to speciality research laboratories, ties to the experimental physicists involved in new device ideas, direct connections to the scientific users of the instrumentation, and facilities for deploying and evaluating the completed instrument. Table I lists the possible partnerships that have a synergistic relationship with the Radio Science Instrumentation Laboratory under the new program concept.

**Table I**

| Group | Radio Science Expertise | Facilities |
|---|---|---|
| UVa Astronomy Department | Astrophysics<br>Observational Astronomy | Optics Laboratory |
| UVa Physics Department | Experimental Physics | Far Infrared Laboratory<br>Machine Shop |
| UVa Electrical Engineering Department | Semiconductor Devices<br>Microwave Components<br>Communication Systems<br>Digital Signal Processing | Semiconductor Device Lab<br>Microwave Research Lab<br>Communications Lab |
| NRAO Central Development Laboratory | Low Noise Amplifiers<br>SIS Mixers<br>Correlation Systems<br>RF Feed Systems | Electrochemistry Laboratory<br>Machine Shop |
| NRAO Green Bank | Astrophysics<br>Radiometer Systems | Radio Observatory Site<br>Outdoor Antenna Test Range<br>Indoor Antenna Test Range<br>Machine Shop |
| NRAO Headquarters | Astrophysics<br>Observational Astronomy | Image Processing Laboratory |

## Funding Issues

It is essential that funding be sought from a variety of sources on order to sustain the laboratory and education program over the long run. Specifically, four channels have been targeted: 1) *Laboratory and Program Creation* - A proposal will be submitted to the NSF Integrative Graduate Education and Research Training Program (IGERT) to acquire sufficient funds to develop the program itself over a period of several years. These funds would offset administrative costs related to course development, pay staff salaries, purchase laboratory equipment and supplies, provide graduate student support, pay partnership laboratory and service fees, and initiate a couple of small scale projects. 2) *Equipment Upgrades* - It is extremely important to keep the laboratory equipment and facilities at the state-of-the-art. A proposal will be submitted periodically to the NSF Major Research Instrumentation (MRI) program for this purpose. 3) *Funding for Individual Projects* - The projects will eventually become the focus of the laboratory and educational program. Funding to support the projects will be sought from NSF Division of Astronomical Sciences, NSF MRI, NASA, ONR, ARO, and many others.

Collaborations with groups outside the Laboratory will be encouraged. 4) *Support for Postdocs and Graduate Students* - Often it would be quite useful to have additional students and postdocs working on a particular project where limited project funding may be inadequate to do so. NRAO has agreed to support a graduate student position and additional support in this area will be solicited from other organizations such as NAIC, SETI Institute, etc.

## Research Projects

The research project forms the core of the educational experience. A project is defined as the complete design, fabrication, evaluation, calibration, and deployment of a particular scientific instrument, experimental apparatus, or prototype. The project might enable a scientist to open a new avenue of research or enhance the scientific return from an existing instrument. It might be to create a prototype system to explore a new idea for a sensitive RF detector or part of a larger instrument for deployment in space. With proper coordination and management several projects could be accomplished simultaneously within the laboratory facilities.

The first step in research project administration is obtaining adequate funding to support the activities. As an example, a researcher interested in a new instrumentation idea can introduce the concept to the Laboratory directors (representing all the partnership groups) and together they device a plan of action. Perhaps the researcher's graduate student could perform the system integration and coordinate the activities under faculty supervision. The new instrument may require a wide bandwidth, low noise amplifier integrated with a special multi-resonant microwave cavity. A graduate student in EE could be assigned this task and detailed activities for this work coordinated through the Microwave Research Lab with perhaps some help from the NRAO - CDL. The instrument may require a special semiconductor device and so this activity is performed by an EE graduate student in the Semiconductor Device Laboratory under the direction of a faculty member there. Evaluation of the device may require facilities at the FIR Laboratory in Physics. Finally, data collection for the new instrument may require using a new digital signal processing algorithm. A graduate student under the direction of the Signal Processing Group in EE may develop the data acquisition and processing boards. With the overall plan in mind a joint proposal would then be written to a funding agency and, if successful, the work would be divided accordingly.

Over the past several years many interesting radio science projects have been brought to my attention and most of which are ideal for this Laboratory setting. Here are a few examples:

1. Pursue a 1 - 2 GHz array feed prototype (NRAO)
2. Research adaptive RFI canceling techniques for astronomy (NRAO, NAIC, SETI, BYU)
3. Develop ultra low noise amplifiers using InP HFETs and dc-SQUIDs (LLNL/MIT)
4. Examine new Single-Electron Transistor (SET) based photon detectors (Yale)
5. Explore new photon detectors based on trapped Rydberg atoms (UVa- Physics)
6. Create an integrated coupling coil with a low noise amplifiers for MRI microscopy (Duke)
7. Develop simultaneous multi-frequency ESR for metal-protein studies (UVa-Physics)
8. Develop a millimeter wavelength polarimeter for ocean surface wave studies (BYU)
9. Explore terahertz oscillations from an HFET for possible LO applications (Montpellier, Fr.)
10. Investigate wide bandwidth (> 50 MHz) ultrasound techniques (UVa - Biomed)

## Education and Training

A unique aspect of the program is its deliberate weaving of graduate education with hands-on research in instrumentation. Key to the success of the program will be its flexible nature permitting a personalized educational and training experience for each student involved. In addition, people skills such as project organization, leadership, communication, teamwork, responsibility, and ethics will be introduced as part of the overall experience.

Once the project is funded a team is formed consisting of both faculty members and graduate students from the various groups involved and a project coordinator is chosen. Periodic meetings are scheduled to keep the team focused. Each student would be required to take courses directly related to their research tasks (see course list in Appendix B and new course outlines in Appendix C). Students will not only learn about their individual tasks but also how their project is integrated step-by-step into the successful instrument and, in some cases, all the students can take part in the instrument deployment and data analysis tasks. The results of the experiment would be shared with everyone involved.

Another important aspect of the educational program is the possible involvement of Chilean students. The new ALMA telescope will be located in Llano de Chajnantor, Chile and there is a growing interest in establishing a partnership program for instrumentation with Universidad Catolica de Chile and Universidad de Chile. The Laboratory program proposed here could provide a catalyst for implementing such an international educational and training program.

## Invitation for Discussion

After talking with you individually over the past couple of months I am very encouraged about the prospects for a successful program at UVa. At present, this document represents only my personal view of how a modern research laboratory in radio science instrumentation with an integrated graduate education and training program should be organized, funded, and administered. Your comments are welcome and encouraged on all aspects of the proposed program.

# Appendix A *Laboratory Equipment List*

**1) Design and Simulation**

Hardware: High end Sun or HP Workstation & High end PC
Color Printer

Software: HP Advanced Design System (MDS)
HP High Frequency Structure Simulator + Empipe3D - EM Simulation & Optimization
HP Momentum - 2D EM Simulator
Matlab - Communications system and digital signal processing
AutoCad - Mechanical drawing
Mathcad - Quick numerical analysis
Spreadsheet program

**2) Clean Micro-Assembly Area**

Wire Bonder
Desiccators
Dry nitrogen distribution
Ultrasonic cleaners
Assembly microscopes
ESD safe soldering stations (thermal, air, and dc current types)
Hot plates and stirring plates
Air cleaning filters
ESD safe workbenchs
Hand Tools: Tweezers, scalpels, scissors, screw drivers, vises, etc.
Supplies: Solders, microscope slides, swabs, solvents, glassware, component packs, gloves, etc.

**3) Prototype System Fabrication Area**

ESD safe workbench
ESD safe soldering stations
High temperature soldering guns
Small drill press
Bench vises
Digital multimeter
Hand Tools: screw drivers, plyers, taps & dies, calipers, etc.
Supplies: solders, wires & cables, heat shrink tubing, wire lugs, connectors, assorted components, etc.

**4) Electronic Testing**

Power Supplies
Oscilloscopes
Spectrum Analyzers
Network Analyzers
Function Generators
Synthesized Signal Sources
Frequency Sweepers
Multimeters
Frequency Counters
Power Meters
Noise Temperature Meter
Control Computer (low end PC)
Curve Tracer
Temperature Controlled Box
Cryogenic Refrigeration System and Test Dewar

## **Appendix B** *Current Courses Related to Instrumentation*

ASTR 534 - (3) (E)

**Introductory Radio Astronomy**

Study of the fundamentals of measuring power and power spectra, antennas, interferometers, and radiometers. Topics include thermal radiation, synchrotron radiation, and line frequency radiation; and radio emission from the planets, sun, flare stars, pulsars, supernovae, interstellar gas, galaxies, and quasi-stellar sources.

PHYS 519 - (3) (Y)

**Electronics**

Study of practical electronics for scientists, from resistors to microprocessors.

PHYS 531 - (3) (E)

**Optics**

A one-semester course on classical linear optics. Topics include reflection and refraction at interfaces, geometrical optics, interference phenomena, diffraction, Gaussian optics, and polarization.

PHYS 822 - (3) (E)

**Lasers and Nonlinear Optics**

Study of nonlinear optical phenomena; the laser, sum, and difference frequency generation, optical parametric oscillation, and modulation techniques.

PHYS 842 - (3) (O)

**Atomic Physics**

Study of the principles and techniques of atomic physics with application to selected topics, including laser and microwave spectroscopy, photoionization, autoionization, effects of external fields, and laser cooling.

EE 541 - (3) (Y)

**Optics and Lasers**

Review of the electromagnetic principles of optics; Maxwell's equations; reflection and transmission of electromagnetic fields at dielectric interfaces; Gaussian beams; interference and diffraction; laser theory with illustrations chosen from atomic, gas and semiconductor laser systems; detectors including photomultipliers and semiconductor-based detectors; and noise theory and noise sources in optical detection.

EE 556 - (3) (Y)

**Microwave Engineering I**

Design and analysis of passive microwave circuits. Topics include transmission lines, electromagnetic field theory, waveguides, microwave network analysis and signal flow graphs, impedance matching and tuning, resonators, power dividers and directional couplers, and microwave filters.

EE 576 - (3) (Y)

**Digital Signal Processing**

The fundamentals of discrete-time signal processing are presented. Topics include discrete-time linear systems, z-transforms, the DFT and FFT algorithms, and digital filter design. Problem- solving using the computer will be stressed.

EE 602 - (3) (SI)

**Electronic Systems**

Explores frequency response and stability of feedback electronic circuits. Analysis and design of analog integrated circuits such as operational amplifiers, multipliers, phase locked loops, A/D and D/A converters and their application to instrumentation, control, etc.

EE 613 - (3) (Y)

**Communication Systems Engineering**

A first graduate course in principles of communications engineering. Course topics include a brief review of random process theory, principles of optimumreceiver design for discrete and continuous messages, matched filters and correlation receivers, signal design, error performance for various signal geometries, Mary signaling, linear and nonlinear analog modulation, and quantization. The course also treats aspects of system design such as propagation, link power calculations, noise models, RF components, and antennas.

EE 621 - (3) (Y)

**Linear Automatic Control Systems**

Provides a working knowledge of the analysis and design of linear automatic control systems using classical methods. Introduces state space techniques; dynamic models of mechanical, electrical, hydraulic and other systems; transfer functions; block diagrams; stability of linear systems, and Nyquist criterion; frequency response methods of feedback systems design and Bode diagram; Root locus method; System design to satisfy specifications; PID controllers; compensation using Bode plots and the root locus. Powerful software is used for system design.

EE 642 - (3) (Y)

**Optics for Optoelectronics**

Covers the electromagnetic applications of Maxwell's equations in photonic devices such as the dielectric waveguide, fiber optic waveguide and Bragg optical scattering devices. Includes the discussion of the exchange of electromagnetic energy between adjacent guides, i.e., mode coupling. Ends with an introduction to nonlinear optics. Examples of optical nonlinearity include second harmonic generation and soliton waves.

EE 652 - (1 1/2) (Y)

**Microwave Engineering Laboratory**

Explores measurement and behavior of high-frequency circuits and components. Equivalent circuit models for lumped elements. Measurement of standing waves, power, and frequency. Use of vector network analyzers and spectrum analyzers. Computer-aided design, fabrication, and characterization of microstrip circuits.

EE 655 - (3) (O)

**Microwave Engineering II**

Explores theory and design of active microwave circuits. Review of transmission line theory, impedance matching networks and scattering matrices. Transistor s-parameters, amplifier stability and gain, and low-noise amplifier design. Other topics include noise in two-port microwave networks, negative resistance oscillators, injection-locked oscillators, video detectors, and microwave mixers.

EE 741 - (3) (SI)

**Fourier Optics**

Presents the fundamental principles of optical signal processing. Begins with an introduction to two-dimensional spatial, linear systems analysis using Fourier techniques. Includes scalar diffraction theory, Fourier transforming and imaging properties of lenses and the theory optical coherence. Applications of Wavefront-reconstruction techniques in imaging. Applications of Fourier Optics to analog optical computing.

EE 774 - (3) (E)

**Advanced Digital Signal Processing**

Topics include a review of matrix analysis tools, the elements of estimation theory, and the Cramer-Rao Bound; spectral estimation, especially nonparametric (incl. filterbank) methods; parametric methods for rational spectra; parametric methods for line spectra; spatial spectral analysis; and adaptive filtering, especially least mean squares (LMS) and recursive least squares (RLS) algorithms.

EE 776 - (3) (O)

**Multi-Dimensional and Array Signal Processing**

Provides the basic background of multi-dimensional digital signal processing with an emphasis on the differences and similarities between the one-dimensional and multi-dimensional cases. Topics include 2-D Fourier analysis, 2-D stability, 2-D spectral estimation, and inverse problems such as beamforming and reconstruction from projections. The theory developed serves as the foundation of digital image processing, and is applied to array signal processing (e.g., radar, sonar, seismic, medical, and astronomical data processing).

EE 825 - (3) (SI)

**Adaptive Control**

Analysis of parametrized control system models, signal norms, Lyapunov stability, passivity, error models, gradient and least squares algorithms for parameter estimation, adaptive observers, direct adaptive control, indirect adaptive control, certainty equivalence principle, multivariable adaptive control, stability theory of adaptive control, and applications to robot control systems.

## **Appendix C** *A Course in Modern Radio Communication Circuits*

This course will be taught through the UVa Electrical Engineering Department. Laboratory exercises may be included.

Course Outline

1. **Intro to Radio Communication Systems**
   + The communication channel
   + Types of modulation
   + Receivers - basic block diagrams
   + Transmitters - basic block diagrams
   + Examples of modern communications
     . Broadcast radio and television
     . Radiotelephone
     . Repeaters and translaters
     . Cellular telephone and other wireless
     . Satellites

2. **Characteristics of Radio Wave Propagation**
   + Nature of radio waves
   + Radio propagation in space
   + The ionosphere
   + Large-scale path loss
   + Small-scale fading and multi-path

3. **Antenna Fundamentals**
   + Function of the antenna
   + Spacial polarization
   + Isotropic antenna concept
   + Directivity and gain
   + Examples of antennas
     . Dipole
     . Yagi-Uda
     . Paraboloids
     . Verticals above ground

4. **Network Noise**
   + Nature of noise
     . Thermal
     . Shot
   + Noise figure and sensitivity
   + Noise in networks
   + Low noise design

5. **Intermodulation Distortion**
   + Gain compression
   + Second and third harmonic distortion
   + Dynamic range
   + SINAD

6. **Frequency Selective Networks and Transforms**
   + Series resonant
   + Parallel resonant
   + Parallel resonant including transformers
   + Impedance matching and filtering
   + Filter delay

7. **High Frequency Amplifiers**
   + Bipolar and FET amplifiers
   + High speed OP Amps
   + Broad-banding techniques
   + Automatic gain control

8. **Hybrid and Transmission Line Transformers**
   + Three winding transformers
   + Transmission line transformers

9. **Power Amplifiers**
   + Class A
   + Class B
   + Class C
   + Class D
   + Class S
   + Class E

10. **Oscillators**
   + Conditions for oscillation
   + Amplitude and phase stability and noise
   + Crystal oscillator circuits
   + Voltage controlled oscillators
   + Relaxation oscillator

11. **Phase-Locked Loops**
   + Linear model
   + Phase detectors
   + Loop filters
   + PLL applications

12. **Modulators and Demodulators**
   + Frequency mixers
   + Amplitude and phase modulation
   + Digital modulation
   + Frequency multipliers

## **Appendix C** *A Course in Radio Astronomy*

This course will be taught through the UVa Astronomy Department and will be integrated together with the current radio astronomy course to form a two semester radio astronomy sequence.

Instrumentation Topics

**1. The Radio Sky**
+ Sources of radiation
+ Radiation types
+ Atmospheric absorption and refraction
+ Observational parameters

**2. Radiation Properties**
+ Field strength and flux
+ Polarization
+ Frequency characteristics
+ Blackbody spectrum

**3. Noise Characteristics**
+ Statistics
+ Spectrum and quantum limits
+ Sqrt(B*t)
+ Correlation

**4. Observational Techniques**
+ Calibrations
+ Beam switching
+ Load switching
+ Frequency switching
+ Mapping techniques

**5. Antennas**
+ Types of antennas
+ Collecting area etc.
+ Antenna temperature concept
+ Near and far sidelobes

**6. Receivers**
+ Types of receivers
+ Heterodyne concept
+ Components
. Transmission lines
. Amplifier
. Mixer
. Local Oscillator
. Filters
. Couplers
. RF switches
. Circulators/Isolators
. Noise source
+ Complex Ohm's law and power match
+ Noise temperature concept

**7. Backends**
+ Square-law detector
+ Integration
+ A/D sampler and sampling theorem
+ Correlator

**8. Fourier Series and Fourier Transform**
+ Rationale
+ Noise representation with Fourier series
+ Complex vector representation
+ FFT
+ Complex sampling
+ Delay and phase concepts

**9. Spectrometers**
+ Filter bank
+ Autocorrelation
+ AOS
+ FTS

**Laboratory Experiments**

A. Time and Frequency Domain of Noise
B. SQRT(B*t) Measurement
C. Sky Noise at Low Frequency (GB)
D. Antenna Pattern and Gain (GB)
E. Filter Properties and Frequency Conversion
F. Hot/Cold Load
G. Sampled Noise