Radio-Astronomical System: Square-law Detectors and RC Integrators

The goal of this lab is to test the properties of a square-law detector and to build a simple RC integrator. A good introduction to radio astronomical instrumentation and terminology geared to undergraduates is at the Haystack Observatory

http://fourier.haystack.mit.edu/urei/tutorial.html

Background and Theory

A radio telescope consists of an antenna (typically a parabola) and a receiver. It differs in a fundamental sense from an optical telescope in that it is not an imaging instrument but rather a bolometer - the output is a measure of the total number of photons incident on the telescope per unit time and frequency. The reason a single radio telescope cannot image radio sources is that the angular structure of radio sources (~arcseconds) corresponds to a linear dimension much smaller than one wavelength at the focal plane. Radio maps are made using radio interferometry, in which the effective angular resolution ($\theta / D$ radians, where $D$ is the interferometer spacing) is smaller than the source size. The signal from the telescope's feed is amplified, filtered, detected, smoothed (integrated) and displayed. A very simplified block diagram of the signal path is shown below:

![Signal Path Diagram](diagram.png)

The present lab is an introduction to the square-law detector and RC integrator box. In addition we will review the use of some electronics test equipment, including the oscilloscope, digital voltmeter, function generator, and circuit 'breadboard'. In the next lab we will design, construct, and build a low pass filter.

A square-law detector is a device whose output voltage is proportional to the square of its input voltage, i.e.

$$V_{out} = a \cdot V_{in}^2 + V_0$$

where $a$ and $V_0$ (~0) are constants which depend on the circuit. Square-law detectors are quite useful for measuring power since the power is proportional to the square of voltage-hence the output voltage is linearly proportional to input power. The simplest type of square-law detector is a signal diode. It has a nearly square-law response only over a limited range of input voltages, so it is important to ensure that the input level is within the square-law range. The output is an DC signal ($V > 0$) but needs to be smoothed to provide a measure of average power.
An integrator or RC circuit smoothes the input signal with an effective smoothing time:

$$\tau = RC$$

The circuit is a simple series connection that looks like this:

The resistor is measured in ohms (Ω) and the capacitor in Farads (F), resulting in a time constant in seconds. The output voltage as can be easily calculated as a function of the input voltage by setting the currents in R and C equal (series circuit) and solving for $V_{out}$:

$$V_{out}(t) = V_{in}e^{-\frac{t}{\tau}}$$

### Experimental Procedure

1. **[Resistor reading and DVM practice].** You will be given a color-coded resistor. Using the color code key on this Web site to determine the nominal value and tolerance of your resistor. Note: Read the color starting on the opposite end from the tolerance color band [no color (20%), silver (10%), or gold (5%)]. The first two bands are the significant digits, while the third is the power of ten to multiply. For example, a resistor labeled with red-violet-orange-silver bands has a nominal value of $2.7 \times 10^4 = 27,000$ ohms ± 10%. Next, measure the resistor using the digital voltmeter and compare. Is the resistor within the specified tolerance?

2. **[Function generator, DVM, oscilloscope practice.]** Adjust the function generator to generate a 20 KHz sine wave. Attach the output to the Pico virtual instrument (VI) using the frequency meter and adjust so the output is exactly 20 KHz. Next, attach the generator output to Channel A of the VI oscilloscope. Adjust the vertical and horizontal traces so that the waveform is locked and clearly displayed. Carefully measure the time interval $t$ between adjacent maxima. Calculate the frequency ($f = 1/t$) and compare with 20 KHz.
3. [RMS versus peak value for AC signals.] Set the VI voltmeter to read AC volts. Read the value of the function generator output. Now measure the peak-to-peak voltage using the oscilloscope. The DVM should give the RMS (root-mean-square) value, which should be $\sqrt{2}$ smaller than the peak excursion (1/2 peak-to-peak value). Measure and compare.

4. [RC Circuit.] Design and build a series RC circuit with a time constant close to 1 msec ($10^{-3}$ sec). Use the same breadboard you used for the filter.

5. Set the function generator to generate a square wave at a frequency of 300 Hz (use the Pico to verify frequency). Display the voltage across the capacitor. Carefully measure the time interval between the maximum and 1/e times the maximum. Compare with RC.

6. [Square-law detector] Build a square-law detector using a 1N34A diode as shown in the diagram at right. A discussion of this circuit is at the following website:


7. Set the signal generator to 20 MHz. Connect the output to the input of the square-law detector. Connect the output of the square-law detector to the Pico input (measure voltage). Measure the output voltage as a function of input power from –40 to –10 dBm in steps of 3 dB.

8. Plot the output voltage versus input power. Fit a least-squares straight line to the data. Is the detector linear over the entire range? What is the maximum input power for which the detector is within 5% of linear?