NEWTON TRAINING (2018):

RADIOMETER , SQUARE LAW DETECTOR and Noise Diodes

Basics and HartRAO implementations.

Keith Jones

Basic Radiometer

- A device for measuring the radiant flux (power) of Electromagnetic radiation (Wiki)
- Dickie in 1946 was one of the forerunners of such an instrument
- He also advocated the close correlation between 'Johnson Noise' in resistors and 'Thermal Radiation of Black Bodies'
- The definition above implies the whole receiver is the radiometer. At HartRAO we tend to consider only the IF amplifier, detector and Voltmeter (or V/F parts) the radiometer.

Useful Formula and Definitions

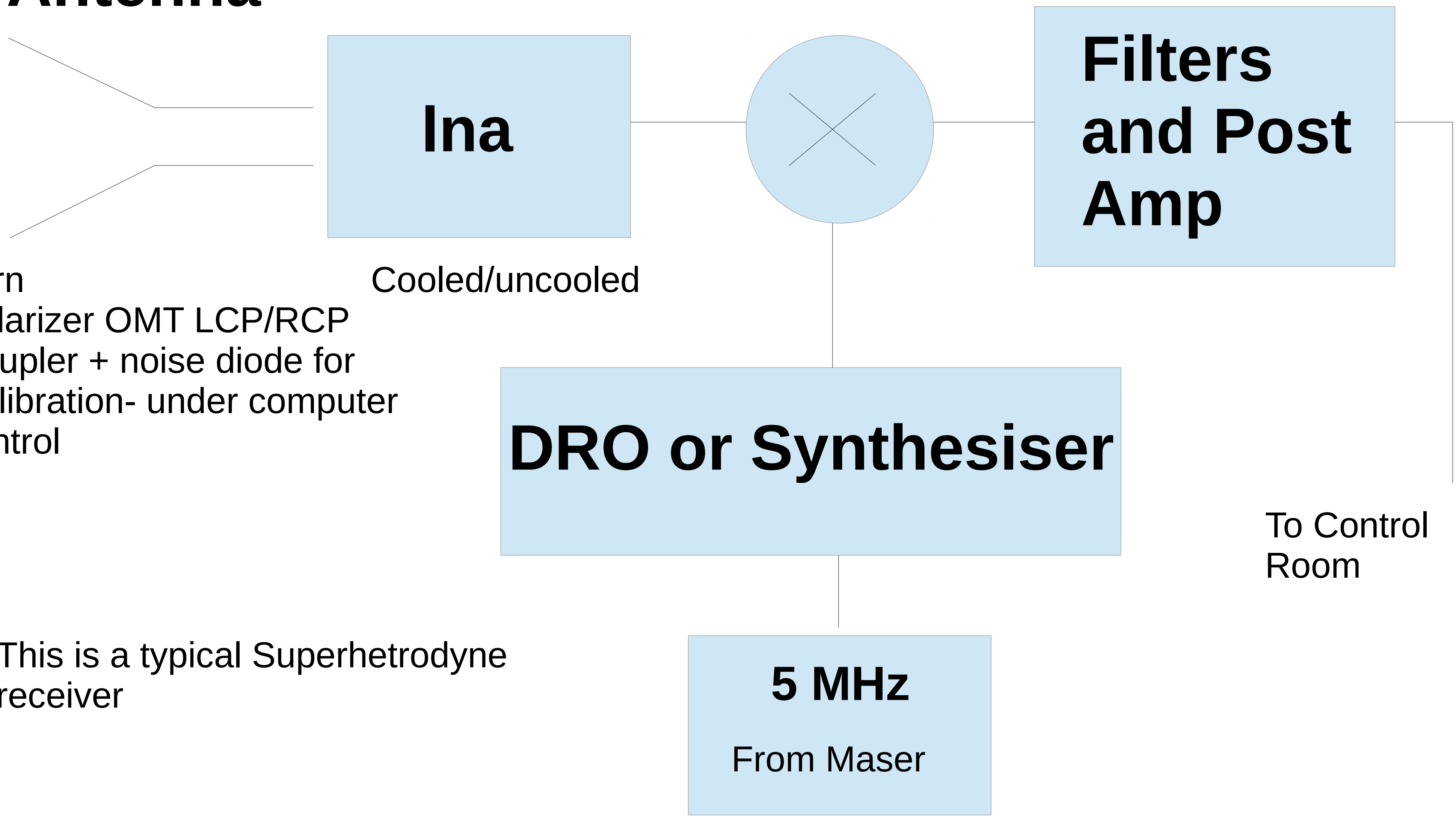
- Flux Density received is measured in Janskys(Jy)- units are **10^(-26) Watts per square meter per Hz** -Krauss
- The significance of this being that received signals tend to be smaller than the inherent noise of the receiver amplifiers and electronics, and are of noise like appearance which makes measurement difficult.
- Thermal Noise Power generated by a resistor **P = kTB** where T is temperature(K) , B bandwidth in Hz and k is Boltzmans constant 1.38 x 10^(-23) units are in WHz^(-1)K^(-1) as an example if a resistor is at room temperature of 290 K then power is -174dBm per 1 hertz of bandwidth. For a 50 ohm resistor this is 0.9 nano volts
- For Amplifiers of gain Gn and Noise Temperature Tn when Cascaded according to Friss:- equivalent noise temperature **T total= T1 +T2/G1+T3/G1XG2** +.... and so on -this means that the first stage is ***Dominant*** and should have the gain as high as possible and its noise temperature should be as low as possible.
- Manufacturers often quote in **Noise Figure (F)** relative to ambient 290K : **F=1 +T/290** and in decibels this is **NF= 10log(F) dB**
- Noise Voltage has **zero mean** and varies randomly on very short time scales (nano seconds) comparable to the inverse bandwidth of the radiometer. If this voltage is squared and averaged over long periods(seconds) then a positive steady output is obtained which is proportional to the incoming noise power. By integrating a large number of discrete noise samples allows the average noise power to be determined to a very low fractional uncertainty (<<1). This enables faint sources that change the antenna temperatures by fractional amounts compared to the total noise power to be detected. The device used to do this is the **Square law detector diode.**

  When a radio telescope looks at a radio source in the sky the receiver output is made up of several components, and is known as the System Noise Temperature **Tsys=Tcmb +Tsource+Tatm+Trec+Tspill**

  Tcmb= microwave background radiation ~2..73K, Tspill= ground radiation spillover, Tatm =atmospheric effects/water vapour, Trec =noise from amplifiers/mixers etc, Tsource = radiation that we are measuring which can be very small compared to the others(<0.1K)
- The main parts of the Radiometer are thus a BandPass Filter, a Square-Law Detector, an Averager (integrator) and a Voltmeter

HartRAO receivers in Cone and Mixers in Dec Room (generic)

26 m Antenna



lna

Filters and Post Amp

DRO or Synthesiser

5 MHz

From Maser

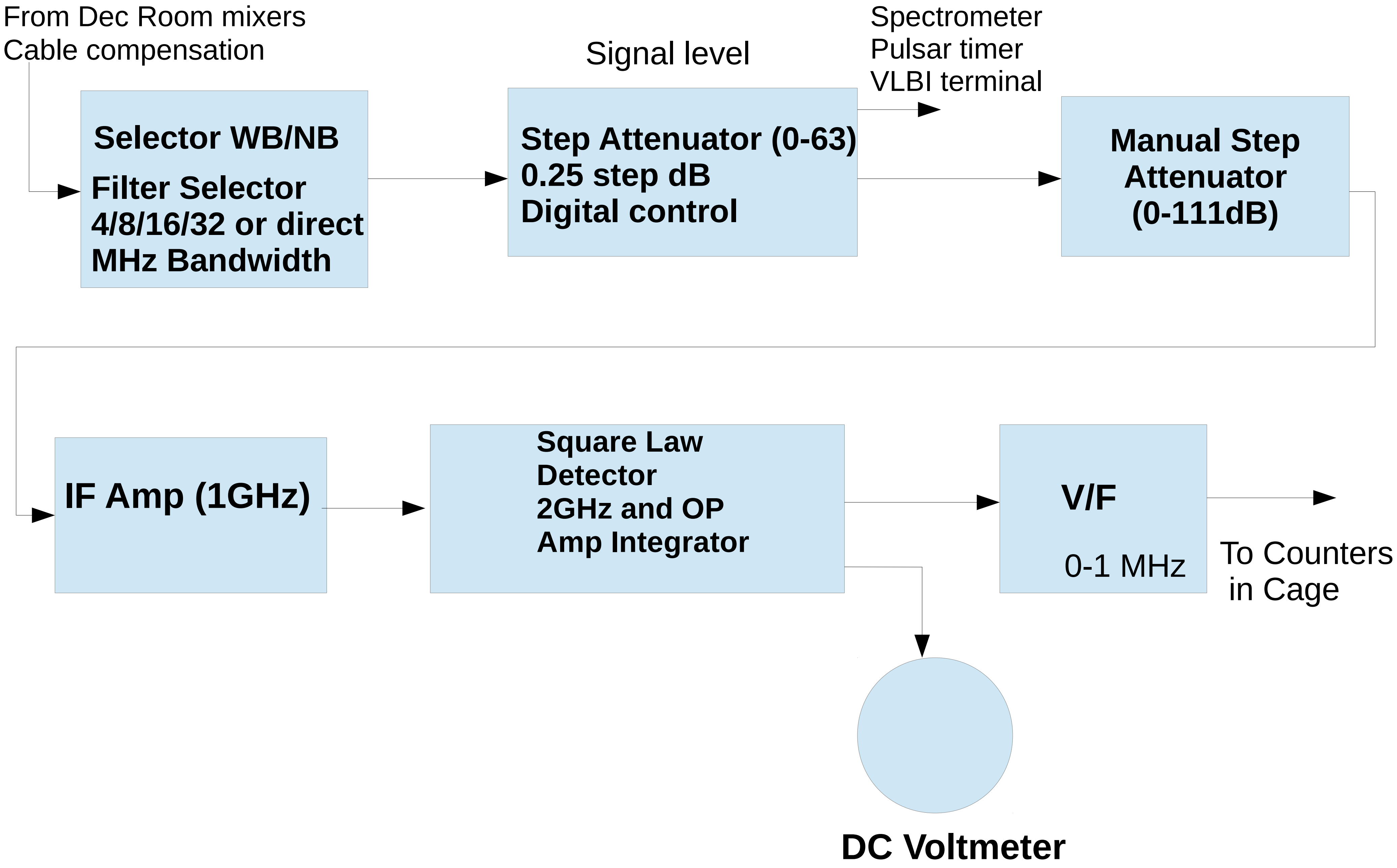
horn
Polarizer OMT LCP/RCP
Coupler + noise diode for Calibration- under computer control

Cooled/uncooled

To Control Room

This is a typical Superhetrodyne receiver

Total Power Radiometer (HartRAO Control room)



From Dec Room mixers
Cable compensation

Selector WB/NB

Filter Selector
4/8/16/32 or direct
MHz Bandwidth

Signal level

Step Attenuator (0-63)
0.25 step dB
Digital control

Spectrometer
Pulsar timer
VLBI terminal

Manual Step
Attenuator
(0-111dB)

IF Amp (1GHz)

Square Law
Detector
2GHz and OP
Amp Integrator

V/F

0-1 MHz

To Counters
in Cage

DC Voltmeter

Dickie Switched Systems

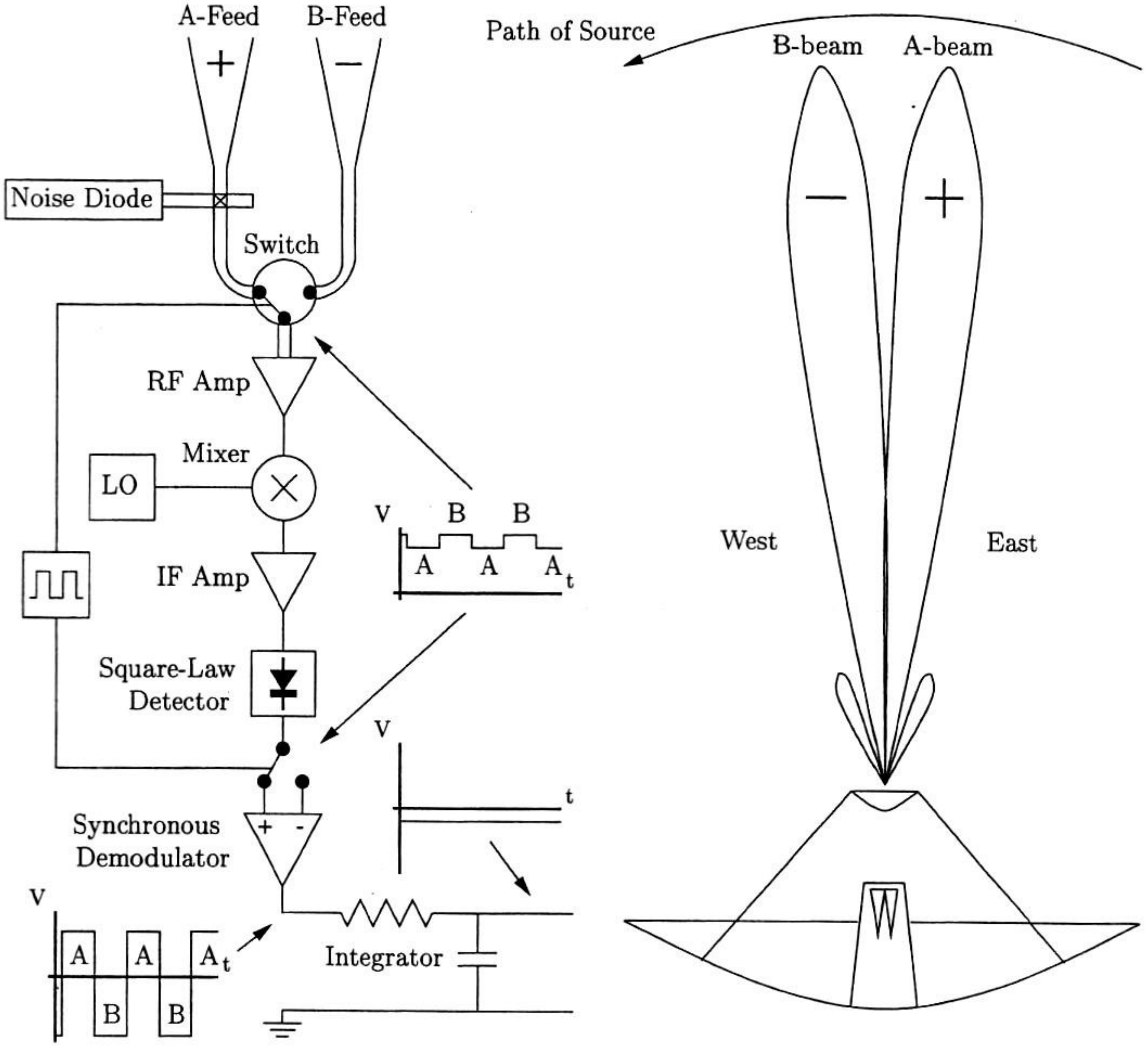
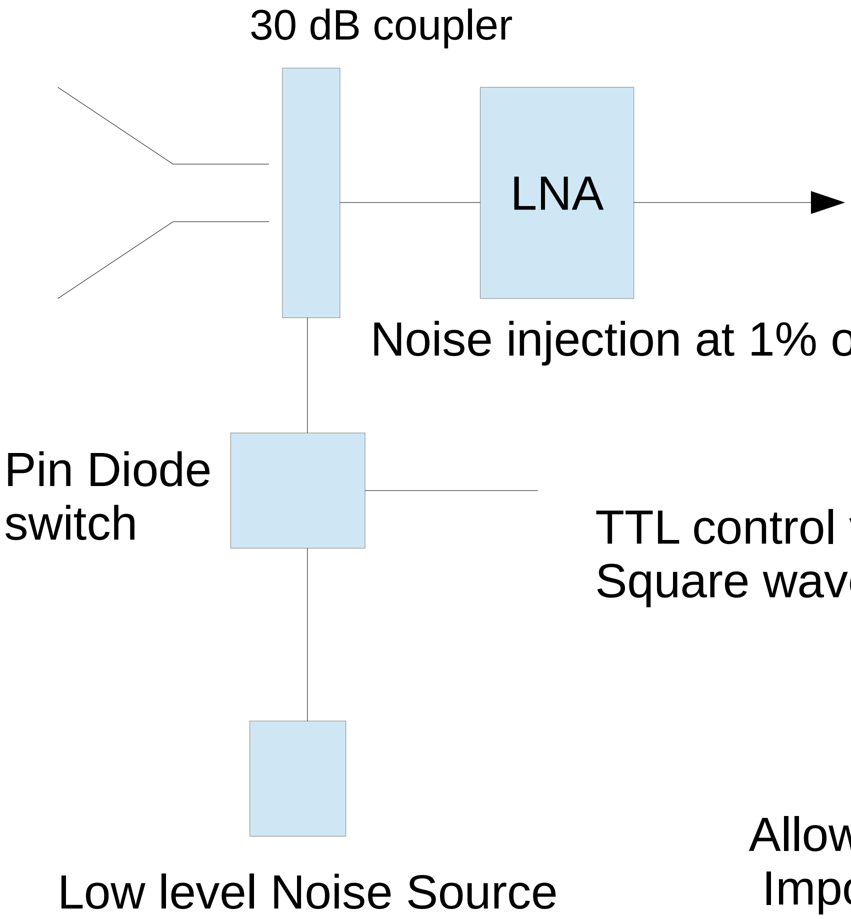


Figure 7: The Dicke-switched dual-beam receiver system used at HartRAO.

One beam is on source the other on sky only. The synchronous demodulator Causes the two beams to be subtracted leaving only the source. ie atmospheric noise effects are canceled out.

Continuous Noise Injection



30 dB coupler

LNA

Rest of Total Power Receiver

Noise injection at 1% of System Temperature

Pin Diode
switch

TTL control via Noise Diode controller interface
Square wave 50 Hz or sub multiples

Low level Noise Source

Allows continuous system calibration
Important for VLBI experiments

HartRAO is presently updating its receivers
to incorporate this methodology

Control Room Radiometers 26 meter Antenna

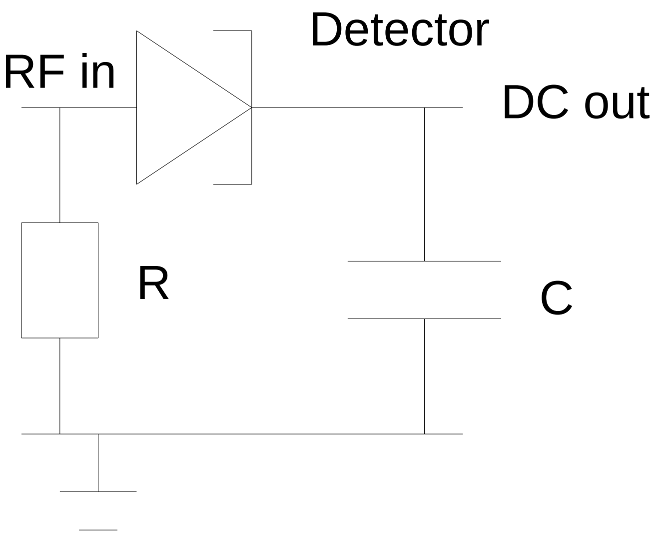
MANUAL STEP ATTENUATOR

Radiometer

15 M ANTENNA S/X RADIOMETERS

Microwave Detector Diode

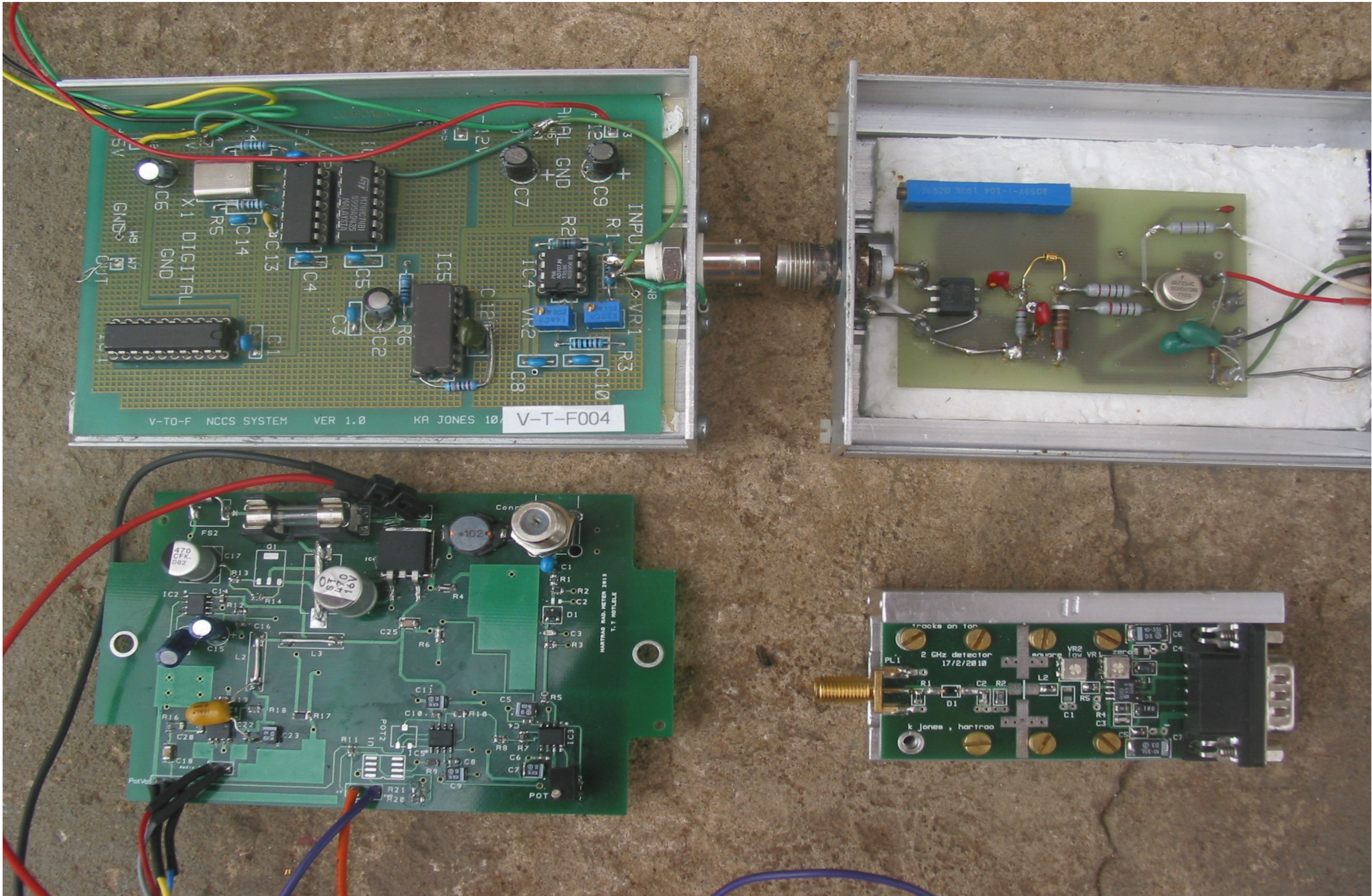
All diodes essentially work in three regions: above 20dBm - Linear, between -20dBm and +20dBm - transition and below -20dBm -the square law region. The later is the region which we require – for converting the incoming signal (power) into some easily measured signal (voltage) -ie if the input power increases by 3dB then the output voltage should double. The basic circuit is as follows:



Resistor R is a wide band Match. (50 ohms)

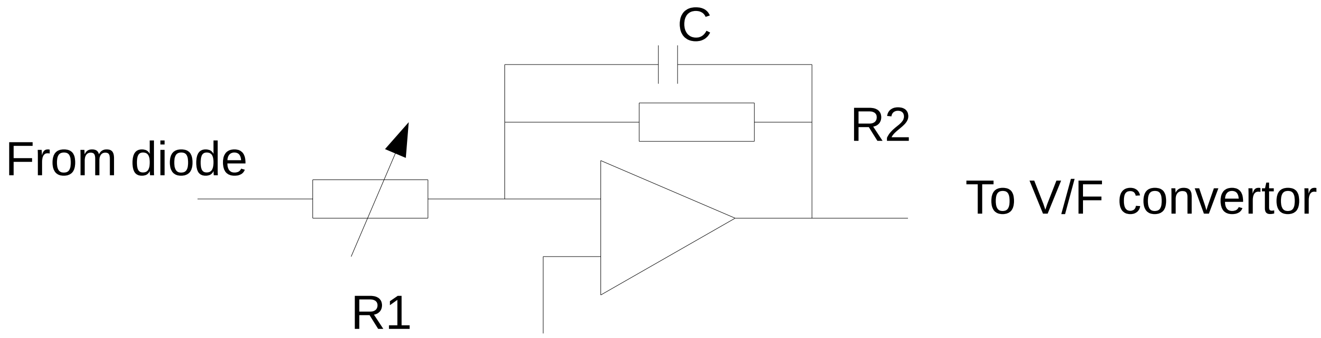
The diode acts like a half wave rectifier, giving positive outputs in this case. The capacitor C is known as the video capacitor and determines the response time to sudden changes in input conditions (noise calibration switch on/off for example) as well as smoothing(averaging) out the signal -commonly referred to as Envelope detection. The choice of Diode is critical, for a wide bandwidth a fast type is essential (low input capacitance in the diode itself). Material type affects the sensitivity of the circuit (curve sharpness) germanium and schottky are good whereas silicon is poor. Tunnel diodes have proven themselves to be robust efficient square law detectors- the first HartRAO detectors used a BD3 germanium back tunnel diode and the later circuits used MBD1057 planar back tunnel diodes,also germanium. The Demonstration Radiometer boards use zero bias schottky diodes which are not so robust, care has to taken to prevent inadvertent input overload from destroying the diode.

Detectors 1975-2014 and VTF 1995



Detector Diode cont

For the dc amplification stage an op amp circuit is used, with a voltage gain of ~100, choice of component is again critical- a good quality instrumentation type, low noise, low offset voltage,temperature stable and a reasonable bandwidth etc. A general purpose LM741 is not suited! Our choice is the OP177 working with a dual voltage rail. Provision for zeroing out any offset voltage when no signal input is present is needed otherwise the square law response will be compromised, particularly at low input power levels.



DC gain = R2/R1
Response time=
R2xC

By 'loading' the output of the detector diode with a variable resistor enables the linearity curve to be adjusted somewhat. Noting that some diodes are better (squarer) than others. The capacitor across the feedback resistor is used for AC integration of the input signal- (active low pass filter).

With the antenna at Zenith (cold sky) the dc output is adjusted with the step attenuators to be 300mV nominal, allowing sufficient (square law) range on strong signals for the detector to work over. Poor settings will lead to the diode operating in its transition or even the linear region.

TYPICAL GERMANIUM DIODE characteristics

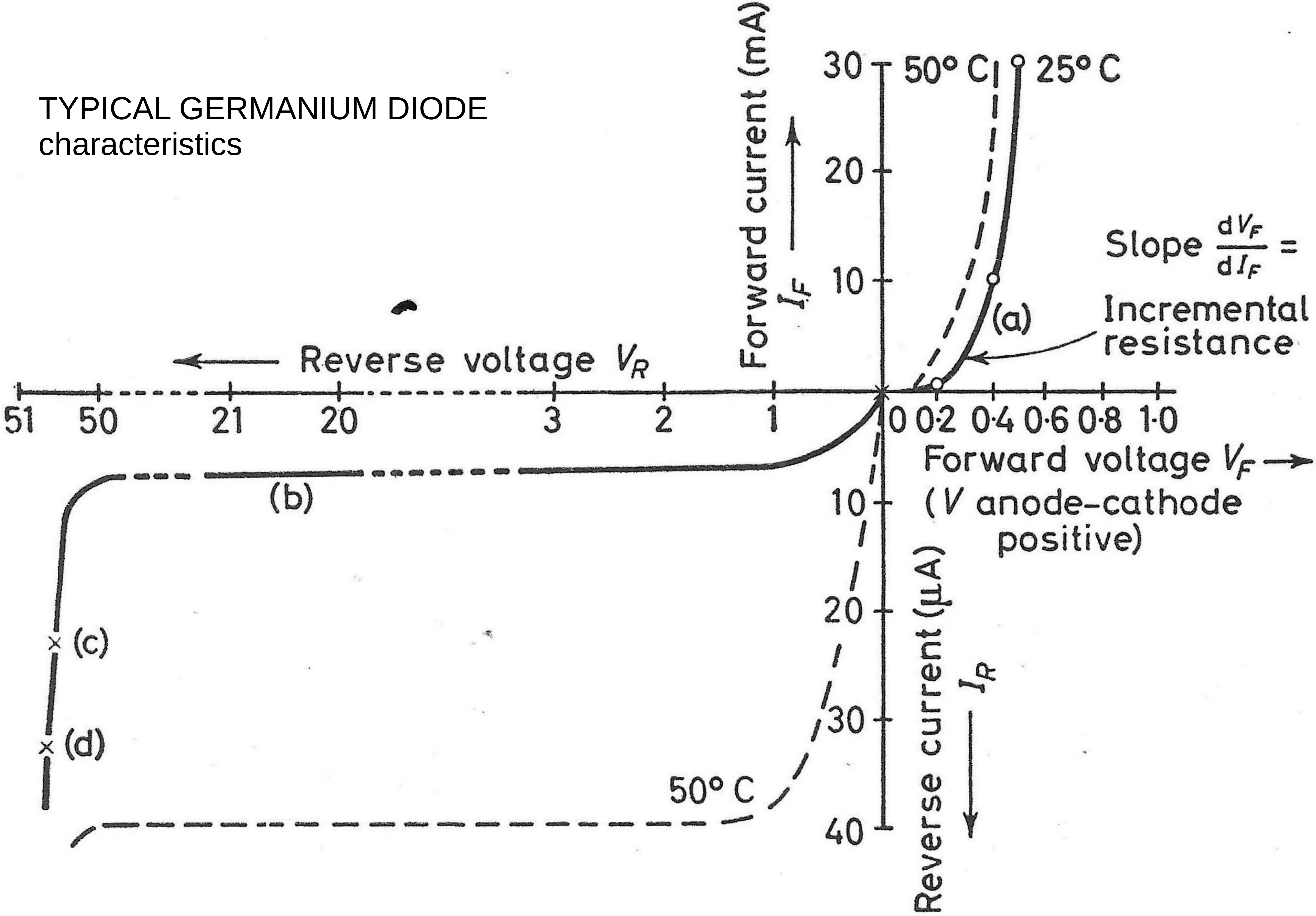
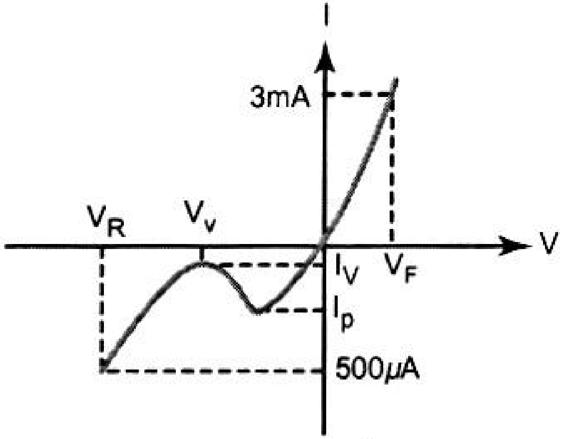
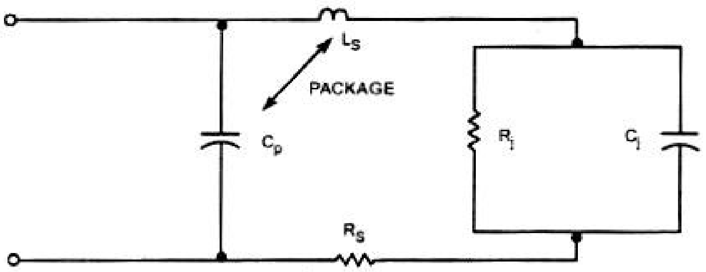


FIG. 1.1 Diode characteristic. Note differing forward and reverse scales

MBD1057





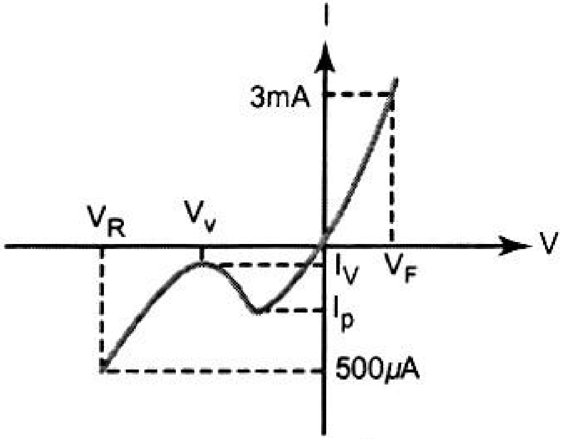
$R_V = R_S + R_j$
$C_T = C_p + C_j$ @ 100 MHz

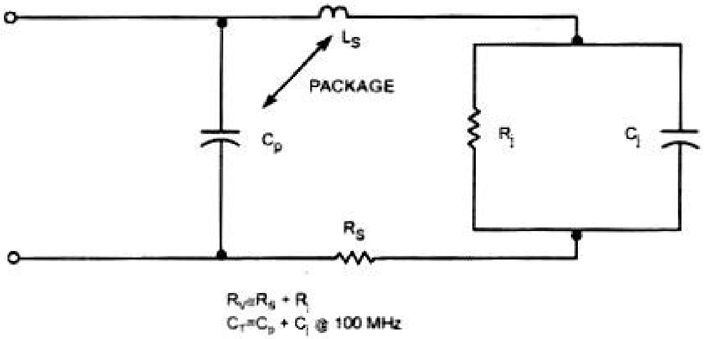
Package

Electrical Specifications, $T_A = 25$ °C

Model	I_P		C_T	γ	R_V	I_P / I_V	V_R	V_F	Package
	MIN µA	MAX µA	MAX pF	TYP mV / mW	TYP Ω	MIN	MIN mV	MAX mV	
MBD1057-E28 / 28X	100	200	0.40	1,000	180	2.5	420	135	E28 / 28X
MBD1057-H20	100	200	0.50	1,000	180	2.5	420	135	H20
MBD1057-T54	100	200	0.55	1,000	180	2.5	420	135	T54
MBD1057-T80	100	200	0.65	1,000	180	2.5	420	135	T80
MBD2057-E28 / 28X	200	300	0.40	750	130	2.5	410	130	E28 / 28X
MBD2057-H20	200	300	0.50	750	130	2.5	410	130	H20
MBD2057-T54	200	300	0.55	750	130	2.5	410	130	T54
MBD2057-T80	200	300	0.65	750	130	2.5	410	130	T80
MBD3057-E28 / 28X	300	400	0.45	500	80	2.5	400	125	E28 / 28X
MBD3057-H20	300	400	0.55	500	80	2.5	400	125	H20
MBD3057-T54	300	400	0.60	500	80	2.5	400	125	T54
MBD3057-T80	300	400	0.70	500	80	2.5	400	125	T80
MBD4057-E28 / 28X	400	500	0.50	275	65	2.5	400	120	E28 / 28X
MBD4057-H20	400	500	0.60	275	65	2.5	400	120	H20
MBD4057-T54	400	500	0.65	275	65	2.5	400	120	T54
MBD4057-T80	400	500	0.75	275	65	2.5	400	120	T80
MBD5057-E28 / 28X	500	600	0.55	250	60	2.5	400	110	E28 / 28X
MBD5057- H20	500	600	0.65	250	60	2.5	400	110	H20
MBD5057- T54	500	600	0.70	250	60	2.5	400	110	T54
MBD5057- T80	500	600	0.80	250	60	2.5	400	110	T80
Test Conditions			$V_R = V_V$ F= 100 MHz	P_{IN} = -20 dBm R_L = 10 KΩ F =10 GHz			I_R = 500 µA	I_F = 3 mA	

MBD1057



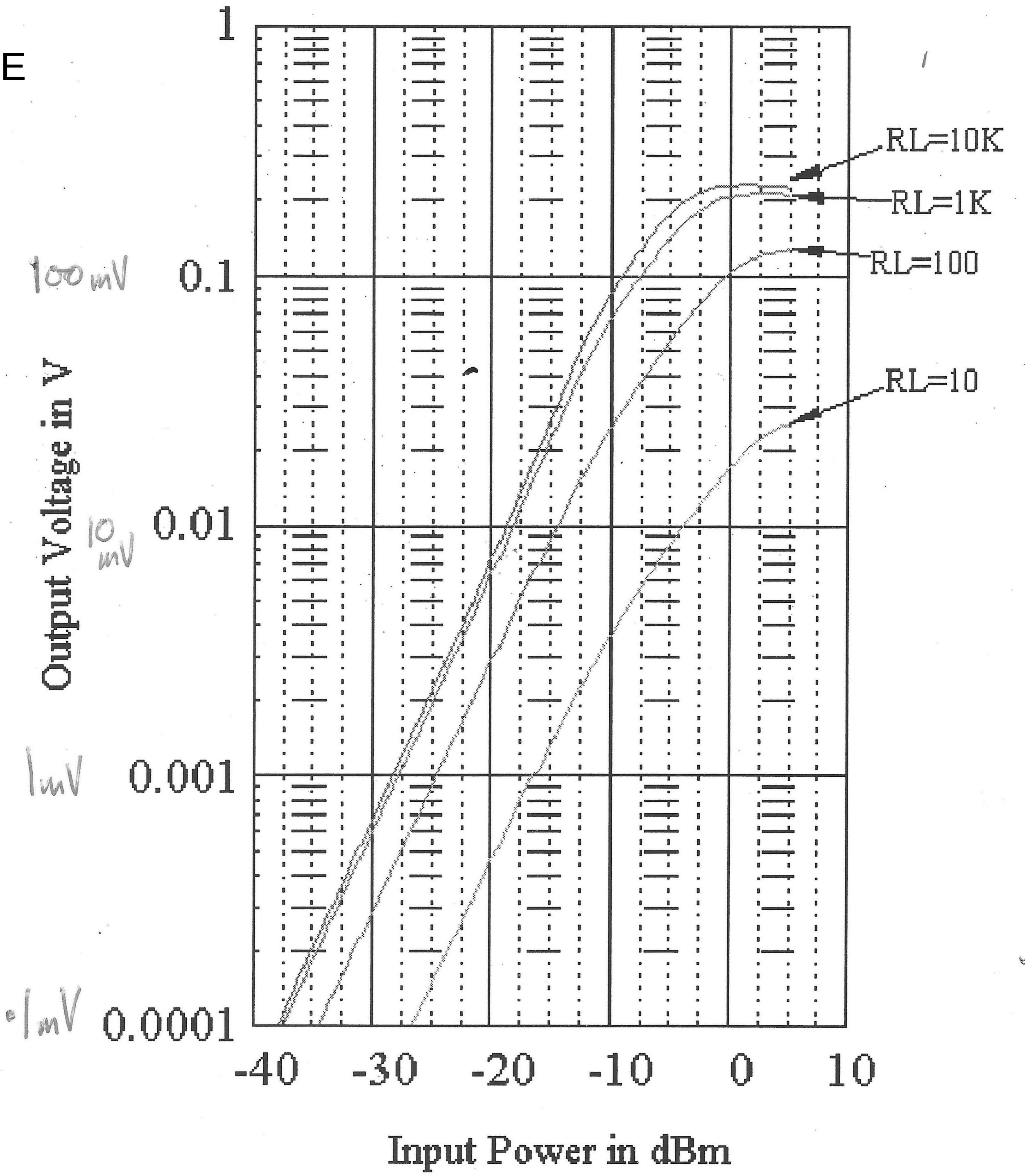


Package

Electrical Specifications, $T_A = 25\ ^\circ C$

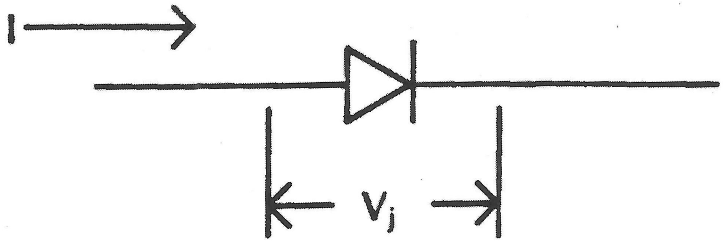
Model	I_P MIN µA	I_P MAX µA	C_T MAX pF	γ TYP mV / mW	R_V TYP Ω	I_P / I_V MIN	V_R MIN mV	V_F MAX mV	Package
MBD1057-E28 / 28X	100	200	0.40	1,000	180	2.5	420	135	E28 / 28X
MBD1057-H20	100	200	0.50	1,000	180	2.5	420	135	H20
MBD1057-T54	100	200	0.55	1,000	180	2.5	420	135	T54
MBD1057-T80	100	200	0.65	1,000	180	2.5	420	135	T80
MBD2057-E28 / 28X	200	300	0.40	750	130	2.5	410	130	E28 / 28X
MBD2057-H20	200	300	0.50	750	130	2.5	410	130	H20
MBD2057-T54	200	300	0.55	750	130	2.5	410	130	T54
MBD2057-T80	200	300	0.65	750	130	2.5	410	130	T80
MBD3057-E28 / 28X	300	400	0.45	500	80	2.5	400	125	E28 / 28X
MBD3057-H20	300	400	0.55	500	80	2.5	400	125	H20
MBD3057-T54	300	400	0.60	500	80	2.5	400	125	T54
MBD3057-T80	300	400	0.70	500	80	2.5	400	125	T80
MBD4057-E28 / 28X	400	500	0.50	275	65	2.5	400	120	E28 / 28X
MBD4057-H20	400	500	0.60	275	65	2.5	400	120	H20
MBD4057-T54	400	500	0.65	275	65	2.5	400	120	T54
MBD4057-T80	400	500	0.75	275	65	2.5	400	120	T80
MBD5057-E28 / 28X	500	600	0.55	250	60	2.5	400	110	E28 / 28X
MBD5057- H20	500	600	0.65	250	60	2.5	400	110	H20
MBD5057- T54	500	600	0.70	250	60	2.5	400	110	T54
MBD5057- T80	500	600	0.80	250	60	2.5	400	110	T80
Test Conditions			$V_R = V_V$ F= 100 MHz	P_{IN} = -20 dBm R_L = 10 KΩ F =10 GHz			I_R = 500 µA	I_F = 3 mA	

MBD 1057
TUNNEL DIODE



Typical Transfer Curve
Output Voltage vs Input Power and RL

Diode Equation



$$I = I_s[\exp(V_j/V_t) - 1]$$

I = diode current
Vj = junction voltage
Vt = "thermal voltage"

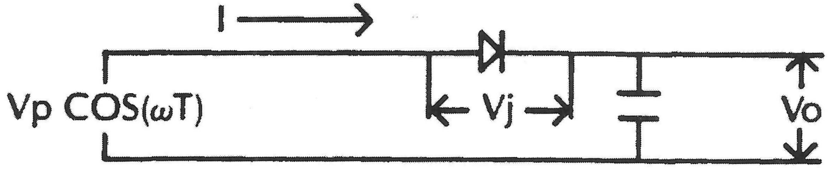
$V_t = nKT/q$
K = Boltzmann constant
T = Absolute temperature
q = Electron charge
n = ideality factor
$(1 < n < 2)$

Is = reverse saturation current
Determined by:
Junction area
materials
temperature

Is changes by 2:1 for temperature change of about 20 degrees C

At low signal levels, all three types of diodes closely obey the equation for the ideal diode, and this will be the starting point for the discussion of detector action. The equation relates the current through the diode to the voltage appearing across the junction. The characteristics of the diode are reflected in the so-called "thermal voltage", Vt and the reverse saturation current Is. At a given temperature Vt will be different for various types of diodes, and this is reflected by the value of the ideality factor n which has a value in the range of 1 to 2. The predominant factor which determines the characteristics of the diode is the value of the reverse saturation current Is. This current is a function of device area, materials used to form the junction, and temperature. The temperature dependence is very important because most of the change in detector performance can be related to variations in Is, which changes by approximately a factor of 2 every 20°C.

Square Law Detection Simplified Analysis



$$I = Is[\exp(Vj/Vt) - 1] = Is[Vj/Vt + \tfrac{1}{2}(Vj/Vt)^2 + \dots]$$

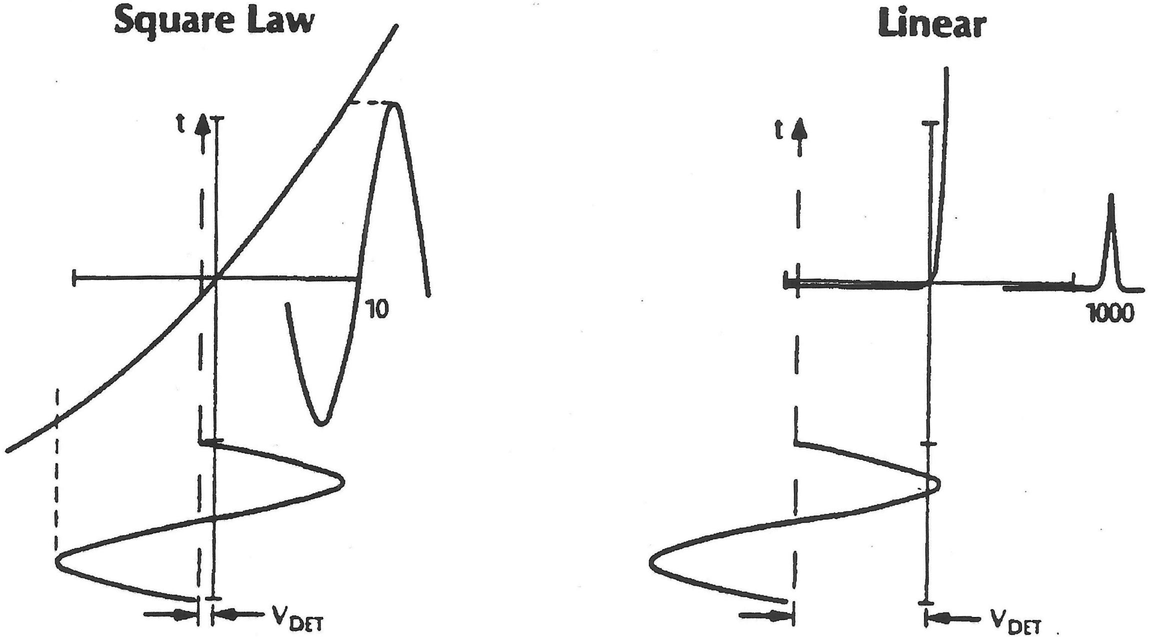
Assume: $Vj = Vp \cos(\omega T)$; $Vo << Vp$; $Vp < Vt$

$$I = \frac{IsVp}{Vt} \mathrm{COS}(\omega T) + \frac{Is}{4}(Vp/Vt)^2\,[1 + \mathrm{COS}(2\omega T)]$$

$$Idc = \frac{Is}{4}(Vp/Vt)^2$$

One of the major applications of diode detectors is to measure either absolute or relative power levels. At low power levels (<−20 dBm), the diode responds to the square of the voltage appearing across the junction so the detected signal becomes a function of power. An approximate but accurate analysis reveals the reason for the square law response. The diode current can be estimated by a series expansion of the diode equation. Upon substitution of a sinusoidal description for the signal voltage, restricting the analysis to signal levels less than Vt, and assuming that the detected signal is negligible with respect to the input voltage, one finds that three dominant terms appear in the expression. Two of these describe the fundamental and second harmonic of the input signal which are bypassed by a capacitor. A dc term which is proportional to the square of the input voltage represents the detected signal. Experimental evidence on a wide variety of detectors confirms the validity of the analysis. It should not be surprising that significant departure from square law is noted for signal levels exceeding 26 millivolts (about −22 dBm in a 50-ohm system) and the detected output level is about 15% of the peak RF input voltage at this power level.

Comparison of Low and High Level Signals

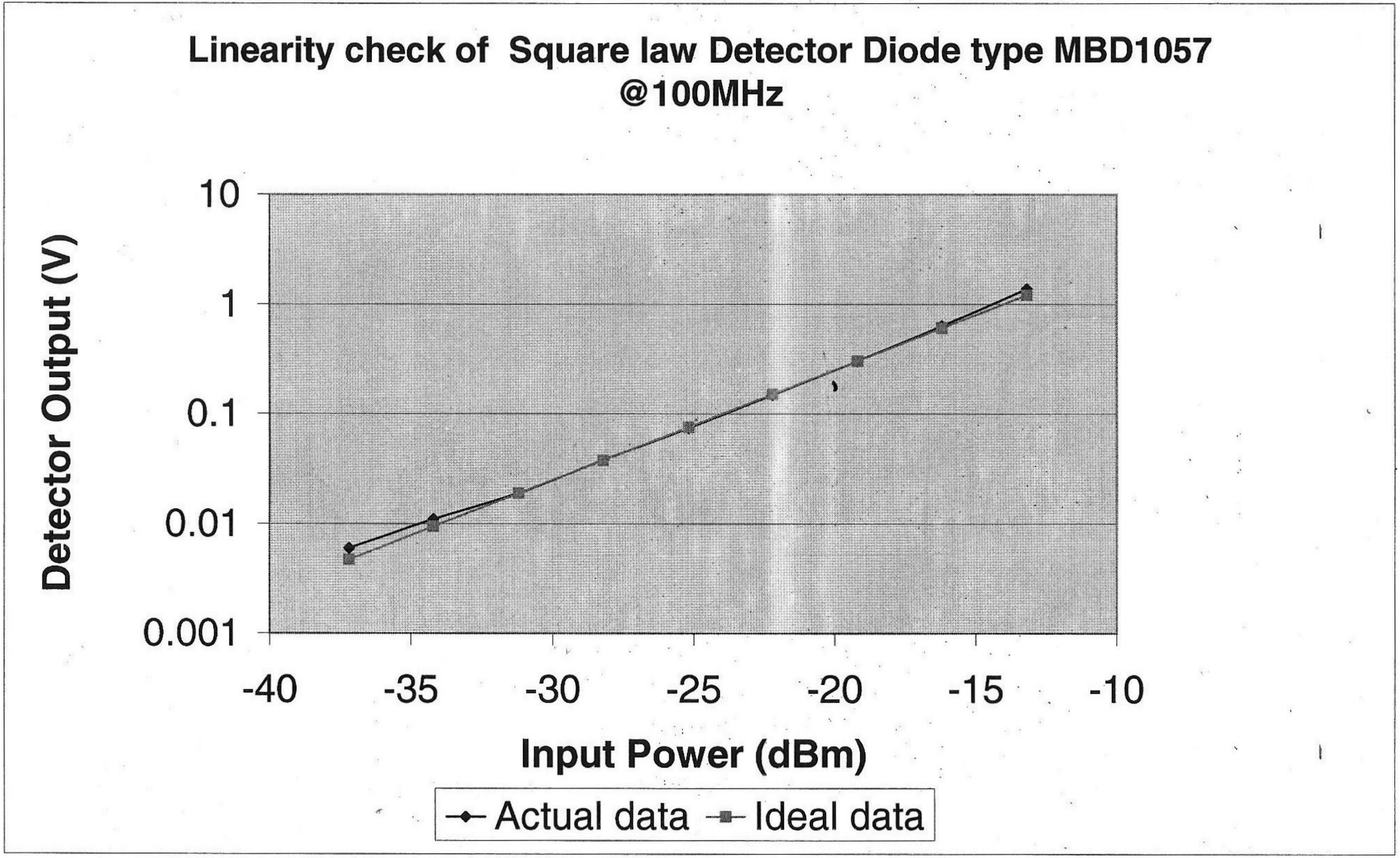


P < 10 microwatts into 50 ohms
Detected voltage proportional to
the square of applied signal.

Power levels greater than 10 milliwatts
Detected voltage proportional to
the peak RF voltage.

Video loading will lower the detected voltage

In the square law region, the waveform of the diode current is almost identical to that of the input signal. Under large signal operation, the diode current waveform becomes a function of input signal level and video output voltage. The output voltage becomes a complicated function of load resistance, power level, and diode characteristics. The key point is that the detection law will undergo a transition from square law to linear. This occurs when the junction voltage exceeds Vt. In the linear mode the diode is acting like the familiar peak detector.


Linearity check of Square law Detector Diode type MBD1057
@100MHz
10
1
0.1
0.01
0.001
Detector Output (V)
-40
-35
-30
-25
-20
-15
-10
Input Power (dBm)
Actual data
Ideal data

V/F and Counters cont.

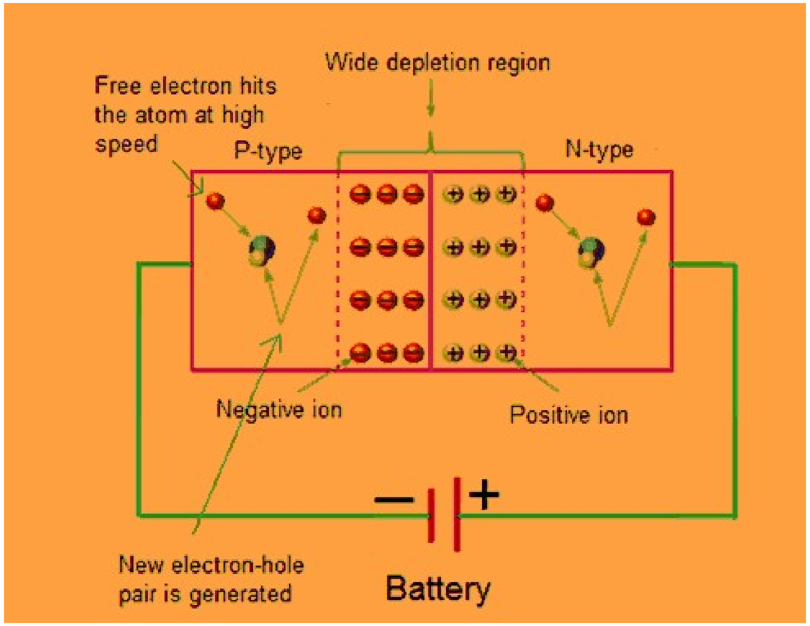
As part of the 26m Antenna Control System a Rack (cage) holds up to 16 counter cards to serve all 7 receivers on the 26m and the S/X receiver on the 15m to count the pulses from all the V/F converters. Each card is individually accessed (read/write) via a 24 bit computer bus. (1 MHz requires 20 bits).

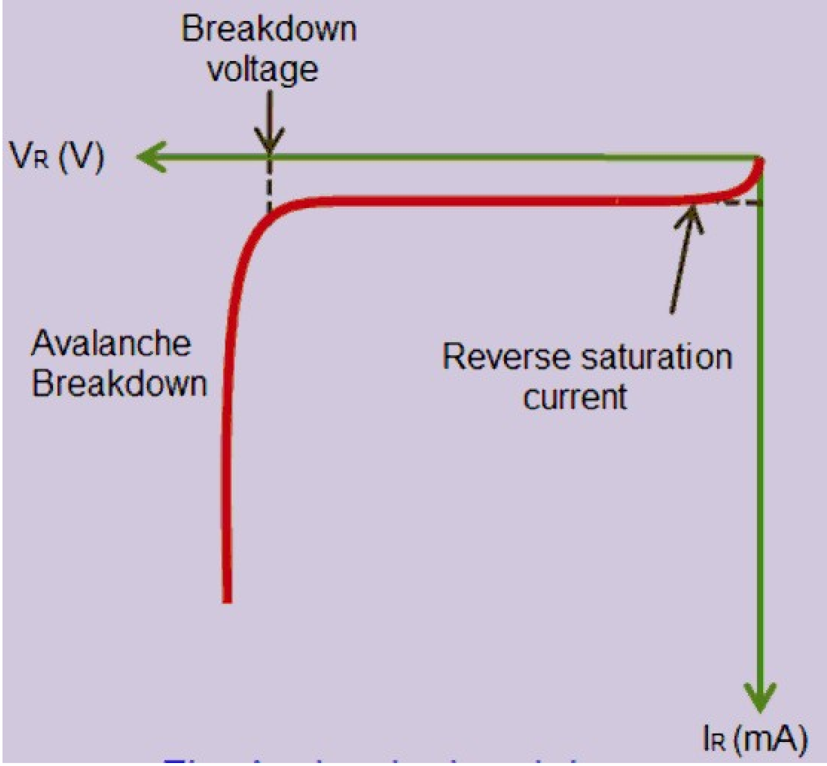
In the timing room a network server transmits a time code signal (at TTL base band level) which is received by a decoder card in the cage. This provides a precise 10ms interval period in addition to the encoded time information. All Instruments (synthesizers) are synchronised to the 5 MHz maser (via their external ref input sockets).

The counter cards use simple Cmos logic counter ic's, and are synced using the *Latch* signal, to reset all the counters and start a new count sequence (every 10ms). The bus is linked to a PC104 I/O card in the Control System PC running Linux RTO. Software running on this PC handles additionally the motor controllers on the 26m, and from 19 bit encoder read outs enables the required pointing of the antenna to a source in the sky all in real time.

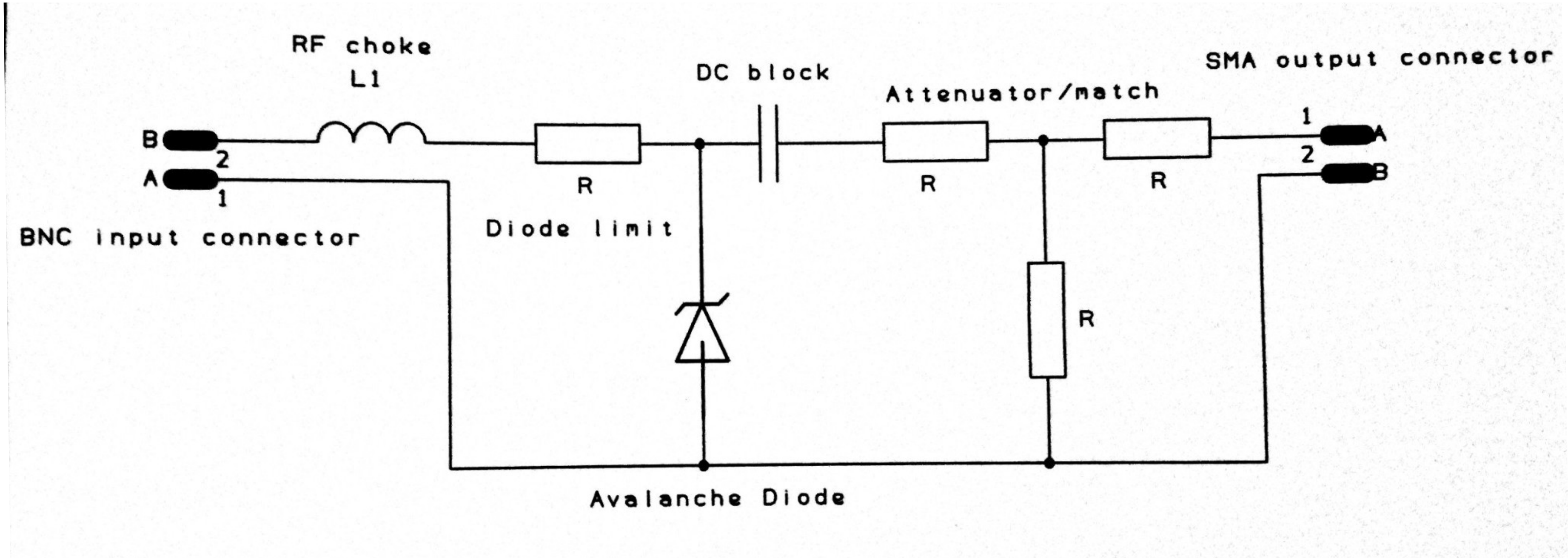
Avalanche Diode

When connected in reverse bias- reverse current is due to minority charge carriers. At a high enough voltage leads to avalanche breakdown.





Typical Design For Noise Diode Generator



The diode can produce random gausian noise of 25-30 dB above a resistor of -174 dBM at room temperature.

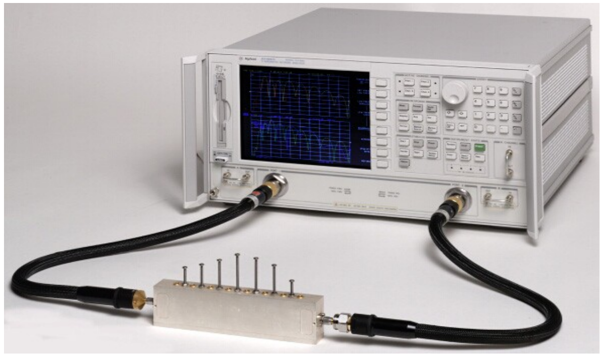
This can be seen on a modern Spectrum Analyser. An oscilloscope would require the noise to be amplified a further 40-50 dB first!

Useful Test Equipment for the Lab.

Signal Generator

Power meter

Vector Network Analyzer



Spectrum Analyzer