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The Concept of Radio Telescope Receiver Design

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Abstract

The receiver system is the heart of a radio telescope. A radio telescope receiver system employs super-heterodyne technique to trap source frequency using associated signal processing devices and performs frequency conversion to yield Intermediate Frequency (IF) signal from which the source information can be extracted. Super-heterodyne receiver which was invented by Edwin Armstrong and patented in 1918 is still the most popular microwave receiver basically because of its high selectivity unlike the earlier regenerative and super regenerative receivers which were prone to drift. The signal power level in radio astronomy receivers is commonly quite low, of the order of 10^{-15} to 10^{-20}W which means that high sensitivity is a major requirement in receiver systems. The performance of the receiver system is fundamental to the overall performance of a radio telescope; hence this paper describes the design concept, the build up and operation of a super-heterodyne radio telescope receiver system.

The Concept of Super-heterodyning

Super-heterodyning entails generating a beat frequency which is usually lower than the original frequencies from the mixing of two or more frequencies that are fed into a detector. In signal processing, this beat frequency is much more convenient to process than the original much higher frequencies and it is usually the sum and difference of the mixed frequencies thereby creating two sidebands, the resulting sum frequency being the Upper Side Band (USB) while the difference frequency being the Lower Side Band (LSB) and in super-heterodyning systems, it is the Lower Side Band that is often used while the Upper Side Band is often ignored. Radio telescope receivers employing this system of frequency mixing beats down the source frequency to generate an Intermediate Frequency (IF) which is more convenient to be processed in order to realise the source profile. This phenomenon is often called frequency conversion.

Why do we need to super-heterodyne? In engineering design, the higher the frequency we intend to receive, the higher the complexity of the circuitry that would be involved. Most devices often fail at extremely high frequencies and this same reason accounts for the fact that we do not have computer microprocessors that operates at such frequencies like 10Ghz. Super-heterodyning help down convert signal frequencies from such a high value where electronic devices would fail. Besides, it generates a fixed Intermediate Frequency (IF) thus allowing all devices to operate at that fixed frequency thereby optimizing circuitry. Another advantage in heterodyning is that it facilitates the lowest sample rates since the centre frequency at digitization can be chosen and could be as low as zero for quadrature sampling. This particularly eliminates the need to design circuitry with devices that would work at wide range of frequencies. In addition, the mixing process helps in signal isolation through arithmetic selectivity. This improves the performance of the Band Pass Filters (BPF) to isolate signals and reject the unwanted bands or interferences.

It is important to know that super-heterodyning does not distort the source signal or the source profile in that during post processing, the source information or profile is retrieved from the amplitude and phase of the signal which are always preserved in the course of frequency conversion. In radio telescope receivers, the frequency mixing is achieved using a Local Oscillator signal with a selective frequency as described in later section of this paper.

Architecture of a Radio Telescope Super-heterodyne Receiver System

A radio telescope is made up of basically the antenna dish system, the receiver system, the back-end systems and the recording systems. Emphasis here will be laid on the receiver system which is made up of basically the Front End section, the RF section and the IF section which are shown in the block diagram below.

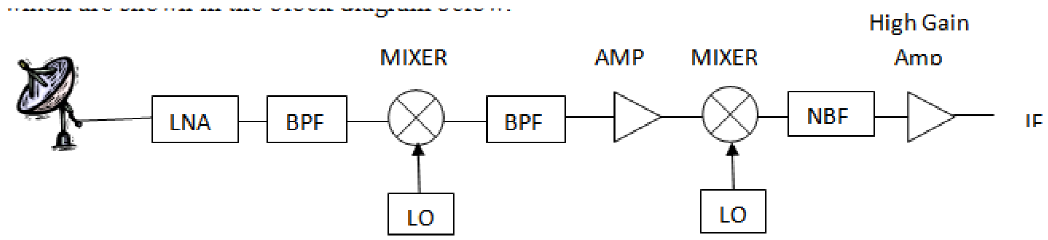

Figure 1: Block Diagram of a Radio Telescope Super-heterodyne Receiver System.

The dish system collects the source frequency and concentrates it onto the feed – horn of the receiver system. In cassegarian dish system, this is often achieved through a sub – reflector at the primary focus of the dish assembly. Wave polarizer which is located in the wave path separates the incoming waves into two components (Left and Right) and guide the separated waves onto Left and Right Dipoles to generate Left and Right polarized RF which is fed into the LNA.

The LNA is a high gain RF amplifier. It receives the weak and faint incoming frequency signal and high - amplifies it to a level strong enough to be detected and processed. It boosts the signal to a level where the amplitude and phase information can be detected and recorded. Noise signal is introduced to mingle with the RF being fed into the LNA by using a noise signal generator, often a noise diode coupled with the LNA for receiver calibration. The purpose for the noise signal is to calibrate the receiver system for the determination of signal detection level. The LNA is extremely critical to the overall performance of any receiver system and it is subjected to hardening in order to increase the signal power while handling much power without being overdriven, else, the incoming weak signal will not be detectable.

In the design of a telescope receiver system, the gain of the amplifier and the Noise Figure(NF) are very critical, the NF is a figure of merit that measures the receivers departure from the ideal state often measured in decibels dB . Typical requirements for LNA in radio astronomy are noise temperature as low as 50K and a gain of 20 – 25dB. Owing to this critical task of LNA, it generates a lot of noise into the receiver system which can shadow the source signal completely when its temperature rises. At extremely high frequency operation like in C and K bands, LNAs require cryogenic condition of operation often around 15K to 22K (-258^{o}C to -251^{o}C) in order to keep the noise level to the minimum and prevent burnout. In operation at longer wavelengths like 18cm, room temperature is adequate for the safe operation of LNA with the aids of heat sinks without introducing much noise into the receiver system. At this stage High Electron Mobility Transistors HEMT amplifiers and RF – SET amplifiers are popularly used to offer high speed and efficiency, high linearity, non – de-phasing for sub Kelvin applications as sensitivity of a receiver system is increased as its added noise is reduced and its bandwidth increased.

The BPF receives the amplified signal and perform frequency selectivity. Since all stray and source frequencies are present at the input of the BPF, the BPF is carefully designed to filter out unwanted frequencies while allowing a band of frequency that accommodate the source signal to proceed for further processing. The range of allowable frequency represents the bandwidth BW of the system. A BPF with a range of allowable frequency of say 1.550 – 1.650 GHz has a BW of 100 GHz; incoming signals below 1.550GHz and above 1.650GHz are filtered – out thereby removing useless frequencies. The choice of the frequency range and BW of the BPF is such that the intended source frequency for observation and processing centres as much as possible on the BW in order to realise a strong source beam pattern.

The Mixer receives the RF signal for frequency conversion. The incoming RF poses a great difficulty in processing owing to its high frequency. The RF is first down converted at this stage in line with the principle of super – heterodyning; a Local Oscillator LO being synchronised by a high precision clock system generates a frequency to mix the RF down to a value that is more convenient for further processing. This results in an Intermediate Frequency IF and an image frequency which are then fed into filter to remove the image frequency which has a high capability of causing interference in the system. This removal prevents in particular, stray transmissions at the image frequency from being picked – up in the system and hence yield a higher level of selectivity at that stage.

Every device involved in the signal processing introduces some losses in the process thereby making it imperative to introduce amplification in – between stages to improve the signal detection. In most applications, the first stage of down conversion takes down the incoming frequency to about 1.4 GHz – 200MHz; after filtering and IF amplification, the signal is subjected to the second stage of down conversion often down to about 200MHz – 30MHz which can be conveniently processed. The signal is then fed into a Narrow Band Filter NBF to remove noise, the image frequency and then isolate as much as possible the incoming signal. The NBF BW is often centred around the incoming IF and the centre frequency should be chosen so that a stable high – gain IF amplification can be economically attained; the frequency has to be low enough so that there would be a steep attenuation characteristic outside the bandwidth of the IF signal in order to keep stray signals acceptably small.

The IF output at this stage is high - gain - amplified to strengthen the amplitude and the phase of the IF for the backend processes which may include digitizing, extraction of the source profile and recording. In practice, the signal can either be detected and recorded immediately after this stage or it could be taken through a filter bank to split the signal into many narrow frequency channels, each of which can be separately detected and recorded.

The bandwidth of a receiver is often set by the bandwidth of first RF filter to dictate the allowable source or incoming frequency. Often, the wider this bandwidth, the better the performance of the receiver; and the higher the noise temperature of the system. Hence, there are always trade – offs at this stage to minimise the noise temperature while allowing a reasonably wide bandwidth. Receiver systems having wider bandwidth while keeping the noise temperature down to an acceptable level would involve more complex circuitry for frequency selectivity, and greater cost.

Receiver bands and their frequency ranges are shown in the table below.

Designation	Frequency	Wavelength
HF	3 – 30MHz	100m – 10m
VHF	30 – 300MHz	10m – 1m
UHF	300 – 1000MHz	100cm – 30cm
L – Band	1 – 2 GHz	30cm – 15cm
S – Band	2 – 4 GHz	15cm – 7.5cm
C – Band	4 – 8GHz	7.5cm – 3.75cm
X – Band	8 – 12GHz	3.75cm – 2.50cm
Ku – Band	12 – 18GHz	2.50cm – 1.67cm
K – Band	18GHz – 27GHz	1.67cm – 1.11cm
Ka – Band	27GHz – 40GHz	1.11cm – 0.75cm
V – Band	40GHz – 75GHz	7.5mm – 4.0mm
W – Band	75GHz – 110GHz	4.0mm – 2.7mm
mm - Band	110GHz – 300GHz	2.7mm – 1.0mm

IEEE Standards 521 - 2002

Signal to Noise Phenomenon

A source signal is of the same nature as the background noise, so the only thing that happen "on – source" is a rise in the average power over the band, which its detectability hangs on the Signal to Noise Ratio (SNR).

The Signal to Noise Ratio SNR of a source is expressed below.

$$SNR = \frac{(on{-}source\ mean) - (off{-}source\ mean)}{off{-}source\ rms} \quad (1)$$

The radio telescope antenna delivers a disturbing noise power to the receiver which depends on the background noise from the sky, atmospheric noise, side lobe noise and noise from the losses of the antenna. The power is expressed in terms of the effective antenna noise (Tsky) in which the signal noise power Ta is not included.

The system noise temperature Tsys is expressed below.

$$\text{Tsys} = Trec + Tsky \quad (2)$$

Where:

Trec is the receiver system temperature.

The total disturbing noise power referred to receiver input is Pn, expressed below.

$$Pn = KbTsysB \quad (3)$$

Where:

Kb is Boltzmann's constant ($1.38 * 10^{-23}$) Joules/K

B is the Bandwidth of the receiver

The Signal to Noise Power SNP is expressed below.

$$SNP = KbTaB \quad (4)$$

Since the signal from a source at reception is noise – like, its presence is reflected in an enhancement of the noise power by Ta, which is an indication of antenna temperature proportionality to source flux.

$$Ta = G.S \quad (5)$$

and

$$G = \frac{Ae}{2Kb} \quad (6)$$

Where:

G is the gain of the antenna

S is flux per unit frequency for source

Ae is effective collecting area of telescope antenna

G ≈ 1K / Jy for Ae = 2700m^2, and 1Jy = 10^{-26} Wm^{-2}Hz^{-1}

Jy is the unit of spectral flux in radio astronomy

Expressing SNR in terms of temperature, from Eqn (1), the off – source mean component is expressed in Eqn (2). The off – source rms after integration is expressed below.

$$off - source\ rms = \frac{(Trec+Tsky)}{\sqrt{Npol.B.\tau}} \quad (7)$$

Where:

Npol is the number of orthogonal polarisation usually 1 or 2.

τ is integration time.

For a bandwidth B, "B. τ" represents the effective integration time.

From Eqn (5), the excess noise temperature, on – source is Ta. Hence from eqn (1) we can express on – source SNR as:

$$SNR = \frac{Trec+Tsky+Ta-(Trec+Tsky)}{\frac{Trec+Tsky}{\sqrt{Npol.B.\tau}}}$$

$$SNR = \frac{Ta}{Trec+Tsky}\sqrt{Npol.B.\tau}$$

From eqn (5), Ta = G.S: Hence:

$$SNR = \frac{G.S}{Trec+Tsky}\sqrt{Npol.B.\tau} \quad (8)$$

If β represents the minimum SNR for a source to be considered detectable, then the minimum detectable flux Smin can be expressed as:

$$Smin = \frac{\beta}{G}\frac{Trec+Tsky}{\sqrt{Npol.B.\tau}} \quad (9)$$

Noise Figure (NF)

The noise figure is a figure of merit of any system at any given frequency; it is expressed as the ratio of the total output noise power density to the portion of that power density engendered by the resistive part of the source impedance, assuming the temperature of the input termination be standard noise temperature (290K). It is a function of frequency, thus NF is the ratio of actual output noise to that which would remain if the device itself did not introduce noise. The performance of radio receiver is specified by this number. The Noise Factor (NFactor) of a system is expressed below.

At 290K,

$$NFactor = \frac{SNRin}{SNRout} \tag{10}$$

Where,
SNRin and SNRout are input and output power Signal to Noise Ratio.

Noise Figure (NF) is expressed as:

$$NF = 10\log\left(\frac{SNRin}{SNRout}\right)$$

$$NF = SNRin\ (dB) - SNRout\ (dB) \tag{11}$$

The SNRin and SNRout in Eqn (11) above are in decibels. The Noise Figure is simply the Noise Factor expressed in decibels.

$$NF = 10\log(NFactor)\ dB \tag{12}$$

The Noise Temperature can be equally expressed as:

$$Noise\ Temperature = 290 * \left(10^{\frac{NF}{10}} - 1\right) \tag{13}$$

The equation below shows the relationship between the Nfactor and the Noise Temperature of a given component (Tcomponent):

$$Nfactor = 1 + \frac{Tcomponent}{290} \tag{14}$$

The ratio of antenna gain (G) and system temperature (T) is an important figure of merit for evaluating the sensitivity of a radio telescope; the higher this ratio is, the better the sensitivity of the system to faint signals. This ratio is often simply measured directly using power meter or a true RMS voltmeter. In principles, the determination of the ratio (G/T) hangs on the determination of a ratio factor Y which is the increase of the noise power when the antenna is pointed first at a cold sky and then to a strong source of known flux density usually the sun.

$$Y = \frac{Noise\ Power\ (sun)}{Noise\ Power\ (cold\ sky)} \tag{15}$$

The relationship between G/T and Y is thus expressed below:

$$\frac{G}{T} = \frac{(Y-1)*8*pi*Kb*L}{S.*\lambda\hat{}2} \tag{16}$$

Where;

Y is the sun noise rise expressed in ratio in eqn (15)

L is the beam size correction factor

S. is the solar flux at the operating frequency in watts/m^2/Hz

λ is the wavelength in meters at the operating frequency

Since radio telescope antenna delivers a disturbing noise power to the receiver as shown in Eqn (2), typical sky temperature is of the order of 3 to 20 K, the contribution to the antenna temperature due to side lobes facing the earth will decrease as the antenna elevation is increased. The antenna temperature typically will be of the order of 25K for elevation angles above 45^o and will perhaps rise to about 90K as the antenna elevation is lowered to about 5^o above the horizon. Hence, high antenna gain and visibly small side lobes is essential for providing a good figure of merit G / T. Figures 2 to 7 below obtained from manufacturers' data show the variation of antenna noise temperature with elevation angle. The figures below show the noise contributions from the antenna dish system is generally higher when position at a lower elevation angle.

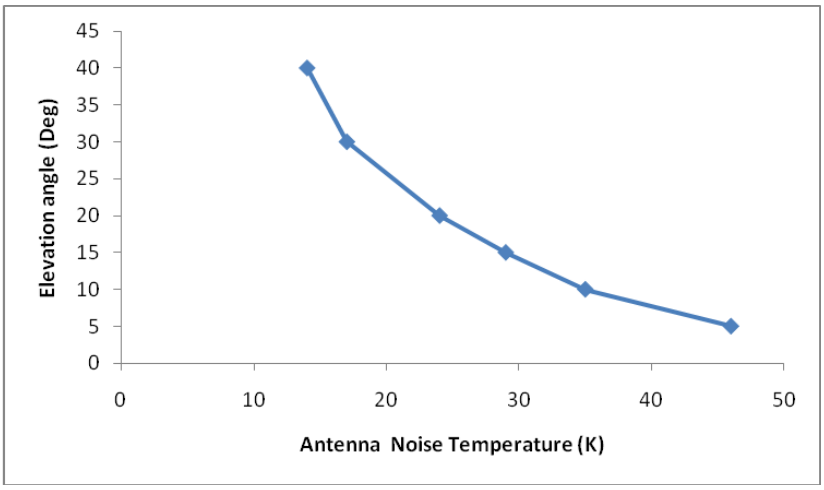

Figure 2: Variation of Antenna Noise temperature with Elevation angle for 10m diameter antenna 8015, C – Band, from Viasat data.

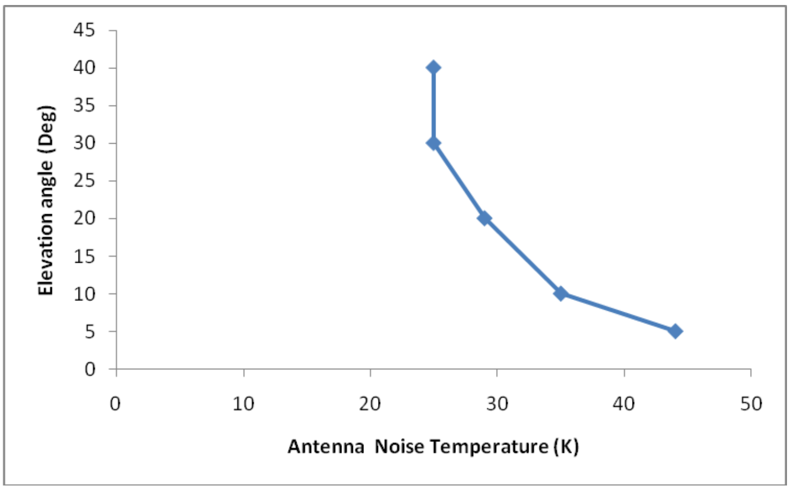

Figure 3: Variation of Antenna Noise temperature with Elevation angle for 18m diameter antenna 18018, C – Band, from Viasat data.

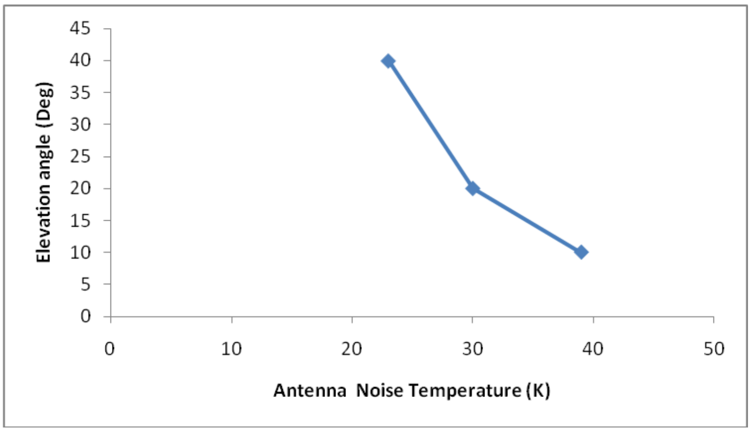

Figure 4: Variation of Antenna Noise temperature with Elevation angle for 3.6m diameter antenna 8136, C – Band, from Viasat data.

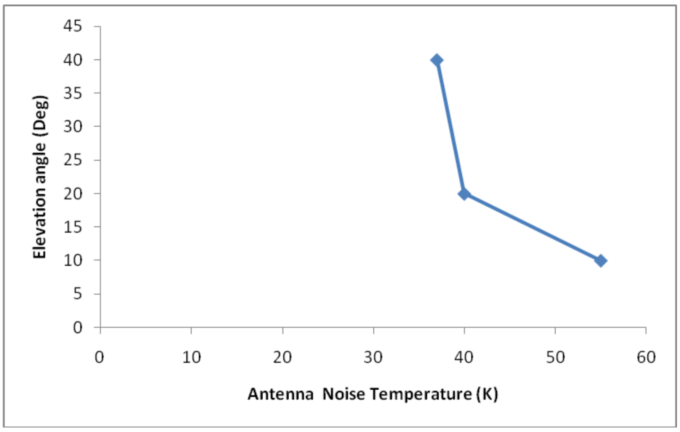

Figure 5: Variation of Antenna Noise temperature with Elevation angle for 3.6m diameter antenna 8136, Ku – Band, from Viasat data.

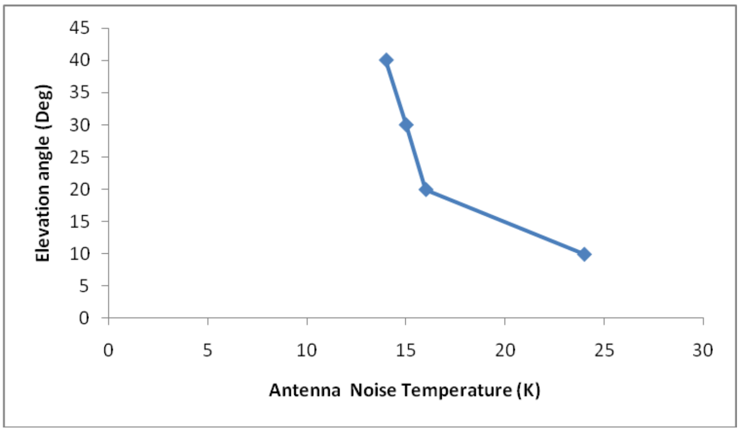

Figure 6: Variation of Antenna Noise temperature with Elevation angle for 3.6m diameter antenna 8136, C – Band, from Viasat data.

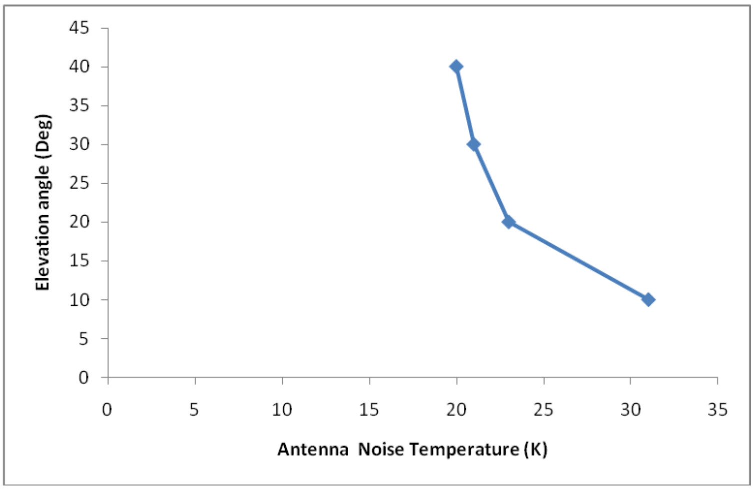

Figure 7: Variation of Antenna Noise temperature with Elevation angle for 3.6m diameter antenna 8136, Ku – Band, from Viasat data.

Conclusion

The performance of a receiver system is critical to the overall performance of a radio telescope. The design of a receiver system demands meticulous judgement on the expected performance of the discrete components as devices like the LNA and Filters are central to the overall sensitivity of the receiver system; the SNR of a system needs to be carefully ensured reasonably high while the devices are tested to ascertain their response at a given frequency. At certain frequencies, the noise generated in the LNA could mask the signal if adequate cryogenic refrigeration is not ensured. Liquid helium is generally used to achieve a cooling down to about 15 – 22K which is adequate for the operation of LNA at higher frequencies. LNAs at L – Bands can be used at room temperatures with the aid of heat sinks to help in cooling. In superheterodyne receiver systems where there are stages of frequency conversions and subsequent amplifications, it is vital to ensure that losses from the associated signal processing devices are not significant to distort the source signal profile while high consciousness is equally given to the realization of a good high Signal to Noise ratio.

References

[1] Zheng X. et al. March 24, 1999. “A new radio spectral receiving system at λ = 13mm in Urumqi Astronomical Station”.
[2] Aaron Koslowski, Warren F. Perger, Jan 13, 1999. “MTU Radio Telescope Project: Design and Fabrication of Radio Receiver”.
[3] IEEE Standards 521 – 2002, “Radio Frequency Band Designations”.
[4] John P. Basart et al. Sept 17, 1998. “IOWA space Grant Consortium, Radio Telescope”.

[5] Ellingson S.W. 2005. Radio Science ASP conference series, vol 345, 2005. “Receivers for Low – Frequency Radio Astronomy”.
[6] Donna Kubik, 2006. PHYS 162 Spring 2006. “Telescope”.
[7] Jarken Esimbek, Yuefang Wu, Hongbo Zhang. Feb 2003. ACTA Atronomical SINICA vol. 44. 2003. “Spectral System of the Urumqi Telescope and Water Maser Studies”.
[8] Tiuri M.E.. May 4, 1964. “Radio Astronomy Receivers”.
[9] Radio Astronomy Supplies, Application Note 5, Jan 2001, “Noise Temperature, Figure and Factor Calculations”.
[10] Lo Y.T, Lee S.W., 1993, “Antenna Theory”.
[11] Richard Flagg, SETI publivations Dept, “Determination of G / T”.
[12] Satellite Internet, www. Satsig.net, “Satellite Antenna noise Temperature and Elevation Angle”.
[13] Dipankar Bhattacharya. Raman Research Institute, Bangalore, 560 080, India. “Detection of Radio Emission from Pulsars”.
[14] Gie Han Tan et al. Telescope and Instrumentation. “ALMA Receivers Invading Chile”.
[15] Xiao yu et al. “Recent development in China”.
[16] Tata Institute of Fundamenental Research. “Giant Meter Wave Radio Telescope”
[17] Raymond Blundeli, Cheuk – yu Edward TongSubmi, “Submillimeter Receivers for Radio Astronomy”.
[18] Microwave Encyclopedia. Microwaves 101. “Superheterodyne receivers”.