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| U.S. Radiocommunications SectorFact Sheet |
| **Working Party:** ITU-R WP 5B | **Document No:** USWP5B31-xx |
| **Ref: New Input** | **Date:** January 22, 2023 |
| **Document Title:** Estimate Radar Bandwidth for Noise Power Calculation |
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| **Purpose/Objective:** The purpose of this contribution is to show how to estimate radar receiver bandwidth, from the radar range resolution, for radars that do not employ an intermediate filter (IF) with a known bandwidth. |
| **Abstract:** There is a need to calculate noise power for interference analysis. Radar systems that do not have a defined IF bandwidth, are known as direct-conversion receiver (DCR), homodyne, synchrodyne, zero-IF or Direct RF Sampling receiver. These are radio receiver designs that demodulate the incoming radio signal using synchronous detection driven by a local oscillator whose frequency is identical to, or very close to the carrier frequency of the intended signal. This contrasts with the standard superheterodyne receiver where this is accomplished only after an initial conversion to an intermediate frequency.  |
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**Estimate Radar Intermediate Filter Bandwidth from ITU-R Recommendations**

**Introduction**

The purpose of this contribution is to show how to estimate radar receiver intermediate filter (IF) bandwidth, from the radar range resolution, for radars that do not employ a known IF bandwidth. This is needed to calculate noise power for interference and compatibility studies.

Radar systems that do not have a defined IF bandwidth, are known as direct-conversion receiver (DCR), homodyne, synchrodyne, zero-IF or Direct RF Sampling receiver. These are radio receiver designs that demodulate the incoming radio signal using synchronous detection driven by a local oscillator whose frequency is identical to, or very close to the carrier frequency of the intended signal. This contrasts with the standard superheterodyne receiver where this is accomplished only after an initial conversion to an intermediate frequency. The following sections provide a short description of radar receiver types and an example of IF receiver bandwidth estimation.

**Receiver Types**

A short description of the receiver types that may be employed by radar systems are as follows.

**Super-Heterodyne receiver.**

In Super-heterodyne or IF receiver architecture, the local oscillator (LO) signal frequency in the receiver mixer is set to be either higher (called high injection) or lower (called low injection) than the desired RF band signal carrier frequency by a fixed frequency difference, called intermediate frequency (IF or *fIF*) so that the frequency translated lower frequency version of the received RF signal is obtained at a fixed frequency of *fIF* in the receiver. The IF stage signal is further converted to baseband using another mixing stage in the receiver. This architecture provides superior filtering performance for the receiver for interferers and channel selection but suffers from the image frequency issue. The size of heterodyne receiver implementation is larger due to various on and off-chip filtering elements in the architecture. Higher size, cost, power consumption, and lower flexibility and reconfigurability are some of the known issues of this receiver architecture as the frequency tuning range of this architecture encounters dead frequency bands in the RF due to various inter-related frequencies for different filtering elements in the architecture. To further increase the image rejection and improve the channel selectivity, two or more IF stages can be added in the heterodyne receiver. Increasing the number of IF stages further limit the receiver frequency tuning range, and increases the size, cost, and power consumption for the receiver system.

**Homodyne receiver, Direct-Conversion Receiver (DCR)**

The simplest of mixer-based receiver architectures is the homodyne (or zero-IF (intermediate frequency) or direct-conversion) receiver architecture in which the LO frequency is set exactly equal to the RF signal carrier frequency so that the resultant signal is obtained at/around DC (direct-current or zero frequency). Still this architecture is relatively simple to implement, and it is more flexibility and easily reconfigurable, low cost, on-chip integrate-able occupying relatively less space in the design real estate and consuming relatively lower power, historically this architecture has been difficult to implement because of known issues of image (for quadrature modulated signals), flicker (or 1/*f*) noise, and fixed and variable DC-offsets due to various signal leakages. Various analog and digital techniques have been developed to address the challenges faced by this homodyne radio receiver architecture. Several receiver design topologies such as conventional zero-IF active or passive switching mixer-based receivers, multi (five or six)-port based receivers, and *N*-path mixer receivers come under the architectural paradigm of homodyne radio receivers.

Some applications for RF-Sampling Data Converters listed below are examples of implementations with usable bandwidth narrower than the entire Nyquist bandwidth:

* 4G Long Term Evolution (LTE) multi-carrier
* 5G massive MIMO (sub-6GHz)
* Microwave backhaul
* Phased-array radars

**Direct RF Sampling Receiver**

In a direct RF-sampling architecture, the data converter digitizes a large portion of frequency spectrum directly at RF and hands it off to a signal processor to examine the available information. This function has traditionally been handled by analog processing (mixers, local oscillators, and their IF filters and amplifiers) into the digital domain. A new class of direct RF-sampling analog to digital converters (ADCs) is being designed in advanced Complementary Metal–Oxide–Semiconductor (CMOS) processes that allow much higher conversion rates with lower power than some previous generations. Additionally, this design approach also enables more digital integration, which is used for a low-power, multi-gigabit serial interface and on-chip digital-down conversion (DDC). Combined, they make for a very size- and power-efficient digital interconnect between the data converter and digital processor.

The ADC sends the data to a Fast Fourier Transform (FFT) for processing. A typical FFT is taken using large/very large number of sample points. For most ADC sample rates, this means that the bin frequency size represents a span of hundreds of Hz or a few kHz. An FFT bin size is defined as the Nyquist spectrum (sampling frequency divided by 2. For example, a 131 MSPS ADC with a 216 (65.5 MHz) sample FFT has a bin size of 65.5 MHz/655000 samples = 1 kHz per bin. So, the noise of the ADC is spread across the Nyquist zone in relatively large bin widths that are 1000 times as large compared to the bin width defined within Noise Spectral Density (NSD). This includes more noise energy in a single FFT bin.

For the example above, if a very large 65.5 Million Samples (MS) FFT were now to be used for the 131 MSPS ADC, the bin width would be 65.5 MHz/65.5 million samples = 1 Hz. In this case, the noise floor of the FFT would be equal to the noise spectral density of the ADC, but the total noise power still has never changed. The same noise power is only spread across finer frequency bin widths.

**Radar Example**

Since the information regarding the digital processing (ADC, FFT etc.) is not usually provided for radar systems in ITU-R Recommendations, we need a simple method to estimate the radar receiver bandwidth for the noise power calculation.

The simplified method will depend on the radar duty cycle and its range resolution. The following are the equations used in the radar receiver bandwidth calculations.

The radar wavelength λ is given by:

 (1)

Where c is the speed of light and f is the radar frequency. From reference 1 equation 3-9, and using the ITU-R radar recommendation parameters of Pulse Repetition Frequency (PRF) in Hz and transmitted pulse width in seconds, the radar unambiguous range in meters is given by:

 (2)

Using the radar antenna azimuth beamwidth and scan revolution per minute (RPM), the radar dwell time or update rate or coherent processing interval CPI or in seconds is given by:

 (3)

From reference 2 equation 4.15, the bandwidth of the filters establishes the Doppler resolution, and hence the velocity resolution. The filter bandwidth is limited to the inverse of the integration time where for pulse doppler we have

 (4)

And for a FM-CW triangular waveform we have

 (5)

For FM-CW modulation with two-phase triangular LFM Waveform, if the pulse modulating frequency is fm, then the waveform has a period of 1/fm. This period is divided into two equal CPIs; however, the CPI duration (1/PRF), the value for , must be somewhat less than a half this period. At the start of each phase of the transmitted signal, returns are still being received from the previous phase of the cycle. Therefore, as the two phase FM-CW transmitted signal starts its up ramp, target returns from the previous down ramp are still being received. Also, at the start of the transmitted down ramp, target returns from the previous up ramp are still being received. During this changeover period, the system cannot assume that returns are those of the current transmitted phase, so the processing must be blanked. The early part of the transmission of the new CPI and the subsequent blanking of returns from the processing are known as *space charging*, since it conveys the image that the volume of space surrounding the radar out to its maximum detection range must be filled, or *charged*, with the new waveform before returns can be processed.

A space charging period must be allowed at the start of any new CPI, whereby the transmitted waveform used during the previous CPI differs from that used during the new CPI. Space charging must be allowed for in all LFM waveforms and for pulsed waveforms when the PRF is changed. When the PRF is constant for pulsed radar then the space charge time is zero.

If the maximum unambiguous range is knows, the time delay for the maximum range is therefore . A value of 50% margin and set as the space charging time, , at the start of each new CPI.

From reference 2 equation 10.6, for pulsed radar with a constant PRF,

 (6)

And for FM-CW modulation with two-phase triangular LFM Waveform with a typical 50% charge time margin is,

 (7)

In the case of pulsed radar and two phase linear FM waveform , adding the space charging, becomes for pulsed radar

 (8)

And for FM-CW two phase linear FM waveform

 (9)

Using reference 1 equation 4.104, the Doppler resolution, in Hz, of the LFM pulse is the same as the that of the single pulse where

 (10)

From reference 2 equation 3-20, the radar target range resolution for unmodulated pulse is given by

 (11)

And for frequency modulated pulse with bandwidth B, the range resolution is given by

 (12)

From reference 2 equation 10-11, the modified range resolution including the charge time is given by

 (13)

Using this modified range resolution, we can solve for the approximate bandwidth, B, of what is to represent the IF bandwidth where the receiver noise power can then be computed to support interference and compatibility analysis when it is not provided in ITU-R Recommendations..

The following is a simple example to show the calculation of estimated bandwidth.

table 1

Example to estimate Bandwidth.

| **Parameter** | **Value** | **Units** | **Reference** |
| --- | --- | --- | --- |
| **Constants** |  |  |  |
| Speed of light | 299792458 | m/s | Constant |
| Boltzmann's constant | 1.38E-23 |  | Constant |
| **Inputs and Assumptions** |  |  |  |
| Waveform type (1=Pulse, 2=LFM pulse, 3=FMCW sawtooth) | 1 | value | ITU-R Rec Input |
| Radar frequency f\_tx | 1.3 | GHz | ITU-R Rec Input |
| Pulsewidth | 102.4 | us | ITU-R Rec Input |
| Chirp Bandwidth (if non-chirp, input zero) | 1.25 | MHz | ITU-R Rec Input |
| Pulse repetition frequency (PRF) | 748 | Hz (pulse/sec) | ITU-R Rec Input |
| Azimuth Beamwidth (Radar FOV) | 2.2 | deg | ITU-R Rec Input |
| Sector Scanned | 360 | deg | ITU-R Rec Input |
| Scan rate in azimuth | 30 | deg/s | ITU-R Rec Input |
| Rotation Rate | 5 | RPM | From deg/s |
| **Calculations** |  |  |  |
| Wavelength l  | 0.2306 | m | Ref-2 Eq 1-1 |
| Unambiguous Range, Assume same as Run | 185.0 | km | Ref-1 Eq 3.9 |
| Update Rate (Dwell time, Coherent processing interval) | 13.636 | sec | θAz\*60/(360\*RPM) |
| The filter bandwidth is limited to the inverse of the integration time or the coherent processing interval Phase Duration (Coherent processing time), tint | 0.07 | Hz | Ref-2 Eq 4-15 |
| Space charging time at the start of each new CPI (without any margin), TSC | 0.00123450 | sec | Ref-2 Eq 10-6 |
| maximum coherent Integration Time, tint (CPI time or Dwell time) | 0.07209883 | sec | Ref-2 Eq 10-7 |
| Frequency Doppler shift (Resolution=1/tint) | 13.87 | Hz | Ref-1 Section 8.1.3, Ref-1 Eq 4.104 |
| Velocity Resolution | 1.60 | m/s | Ref-2 Eq 4-16 |
| Range Resolution (Pulsed or Chirp Waveform) | 119.92 | m | Ref-2 Eq 3-20, 3-21 |
| Approximate Bandwidth to compute noise power | 1.2936 | MHz | Ref-2 Eq 10-11 |

**Some Parameters Meaning**

The following is a list of some radar parameters.

|  |  |
| --- | --- |
| **Mean Transmitter Power** | The average power radiated by the transmitting antenna Reference Range and Target Target’s radar cross-section (reflection strength) at which radar achieves desired detection probability specified at a given distance (reference range) |
| **Transmitter Bandwidth** | The total spectrum spanned by the transmitter Range Resolution Forward distance required between two point targets to resolve into two detections  |
| **IF Receiver Bandwidth** | The Intermediate Filter (IF) bandwidth used to calculate the noise power. |
| **Range bins** | Discrete samples in time are converted to range bins |
| **Compression gain** | The net gain in power resulting from isolating a target’s power in range  |
| **Carrier Frequency** | Frequency of the RF carrier  |
| **Noise Factor** | The ratio of the system output noise relative to thermal background noise.  |
| **Duty Factor** | The ratio of time in which the system transmits  |
| **FOV Azimuth** | Angular width of area within main-beam of radar in horizontal direction  |
| **FOV Elevation** | Angular height of area within main-beam of radar in vertical direction  |
| **Azimuth Resolution** | Horizontal angle required between two point targets to resolve into two detections  |
| **Range Rate Limits** | Minimum and maximum detectable per-second change in relative range between ego vehicle and target |
| **Dwell time** | The time that an antenna beam spends on a target, depends predominantly on the antennas horizontally beamwidth and the turn speed of the antenna. If we assume, that a well designed parabolic antenna got a beamwidth of 1.6 degrees, the full circle of 360 degrees is divided by 360°/1.6° = 225 different directions. 5 seconds divided by the number of 225 gives a dwell time of 5 s / 225 = 22.22 milliseconds. |
| **Maximum unambiguous range (Rmax)** | Is the longest range to which a transmitted pulse can travel out to and back again between consecutive transmitted pulses. The relationship between the PRF or their reciprocal value interpulse period T (PRT) and Rmax determines the unambiguous range of the radar.  |
| **Target Speed** | Speed Limits for Radar analysis is set such that for Aeronautical Radio Navigation Systems (ARNS), the target speed limit is between 20 and 666.74 knots (46.3 to 1234.8 km/hr) |

**Some Radar Types**

Radars use complex technologies for many applications and for various purposes. Radar systems can be classified under various categories. This following is a list of some of the most common non-military radar systems employed today that could use receiver systems that do not include an intermediate filter (IF) in their receiver design.

Air Traffic Control Radars: Air traffic control radars are used both at civilian and military airports. Airborne radar is designed specifically to meet the strict space and weight limitations that are necessary for all airborne equipment. Even so, airborne radars develop the same peak power as shipboard and shore-based sets.

Air Surveillance Radar Sets (ASR): These radars are used for the identification of aircraft, determination of aircrafts approach sequence and for individual aircraft approach controls by Air Traffic control operators. These radars are used under all weather conditions.

Surface Movement Radar (SMR): Surface Movement Radar (SMR) is the most widely used surveillance system for airport surveillance at present. SMR refers to primary radar that provides surveillance cover for the maneuvering area, which is defined as that used for the take-off, landing, and taxiing of aircraft, excluding aprons.

En-route Radars: En-Route Radar is a special type of air traffic control radar developed for en-route control of airspace. It can be used to monitor air traffic outside the special control areas near airfields.

Precision Approach Radars (PAR): The Precision Approach Radar guide aircraft to safe landing under conditions approaching zero visibility. By means of radar, aircraft are detected and observed during the final approach and landing sequence. Guidance information is supplied to the pilot in the form of verbal radio instructions, or to the automatic pilot (autopilot) in the form of pulsed control signals.

Weather Radars: The weather data it finds could be used both for approach support and for feeding into the wider weather data concentration systems. The antenna rotation rate between systems is quite variable (3 to 6 rpm is common). Assuming multiple elevations are used, the weather picture gathered might be updated with a frequency of one minute and upwards (this depends on the complexity and number of the elevations required and the antenna rotation rate). Radar in recent years has become an important tool for the measurement of precipitation and the detection of hazardous weather conditions.

Speed Gauges: Speed gauges are very specialized CW-radars. A speed gauge uses the Doppler- frequency for measurement of the speed. Since the value of the Doppler-frequency depends on the wavelength, these radar sets use a very high frequency in K-Band.

Non-Destructive Material Test: A special radar can be used to penetrate material to detect material-defects.

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