Modeling of an Airport Traffic Control (ATC) Radars Using Mathcad

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Abstract— Air traffic control systems condensed ATC, are faculty liable for the protected, methodical, and quick progression of air traffic in the worldwide aviation authority framework. Typically positioned in airport regulation focuses and control towers on the ground, they screen the position, speed, and elevation of an airplane in their doled-out airspace outwardly and by radar, and give headings to the pilots by radio. The place of air traffic regulator requires profoundly specific information, abilities, and capacities. Therefore, it’s very important to draw and analyze the model for that system. In this paper an Air Traffic Control (ATC) radar mathematical model is built using Mathcad software. The model has the capability of taking into account various radar parameters and converting them into Mathcad codes. Calculations throughout the model are based on basic theoretical equations as well as empirical engineering formulas which give acceptable error tolerances. Results are displayed graphically, particularly the maximum radar range for various essential radar parameters such as the probability of detection, probability of false alarm, and several integrated pulses.

Keywords: ATC Radars, Generalized Detector (GD), Signal-To-Noise Ratio (SNR), Digital Radar Receivers.

I. INTRODUCTION

The increasing demands of air traffic, necessities to have a reliable control as well as management of aircraft movements to obtain a safe flying. It is important that aircraft land safely and it is equally important that they be safe during flight. Air traffic control (ATC) continued to grow and accordingly tracking radars grew as well. ATC radars recently track both aircraft and hazardous weather. Moreover, ATC radars also use the Doppler effect to separate moving and stationary targets and can also measure storm velocities. Accurate positions of aircraft are obtained by using the Global Positioning System (GPS) which is very useful in landing and taking off control of aircraft, particularly at very busy airports [1,2].

ATC radars are in general can be divided into Terminal Radar Approach Control (TRACON) which are responsible to direct aircraft during departure, descent, and approach to and from airports. Other types of radar are the En Route controller that is responsible to direct the aircraft during the high-altitude main part of their flights. ATC radars always remain one of the most complex critical management despite the advancements in technology and science and this is mainly due to the interaction between human and technical systems. Several other control systems operate very well, but there is a possibility that they stop at a certain moment. There is a possible way to overcome this problem is by adopting a model for the ATC radar so that to operate and test this radar in various conditions. Interrogation signals emitted by secondary radars are considered as part of an ATC system that directs aircraft safely. Secondary radars receive the answers using transponders carried onboard by aircraft in the vicinity. Real-time signal processing of secondary radar, active or passive radars enables the identification of individual aircraft including specific data such as destination, number of passengers, altitude, etc. Primary and secondary radars signal together allow for a reliable approach as well as area control [3,4]. Figure (1) shows a picture of primary and secondary ATC radar antennas.

The main decisive element is air traffic control radar systems, which provide ATC authorities with a comprehensive overview of the situation and which guide individual aircraft safely to their destination.

The major importance of this paper is to simulate the ATC with different simulation programs that can give more accurate results that can help all airports to find the best solutions for the system.

The rest of the paper is structured as follows, section two shows other researchers’ works on ATC, section three introduces the proposed methodology, section four presents experimental results, and finally, section five concludes the paper.

II. Related Work

Different program simulator was used to simulate and receive better results for the ATC, in [3] a simulation was presented of the MTI design for the radar system, that shows how the signals of the MTI radar components process, generated and function. The results show a deep understanding of building the system in real life, while [4] shows the variation of target model effect on ATC radar system, and the result gives non-variation targets can give higher range than the variation targets, while the SNR received are very accurate. The researcher in [5,6] designs an ADS-B radar receiver using dipole antenna receiver, RTL-SDR receiver, Bandpass filter, raspberry pi 3, and display screen. The full system was written in a MATLAB programming simulator. The results show the altitude, heading, speed, flight, longitude, message, and time interval are determined, and also improving the adaptability of the ATC system operations by the collected information for the airplanes.

III. The Air Traffic Control (ATC) Radar

The Air Traffic Control ATC radar framework administration is used for hindering effects between planes on the moving area among planes and hindrances, and helping and keeping a methodical movement of air traffic.

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A. Components of ATC Radar System

The Air Traffic Control Radar (ATC-Radar) is the umbrella term for all radar gadgets used to get and screen common and military air traffic in Air Traffic Management (ATM). These radars are normally fixed radar frameworks that have a serious level of specialization and the normal uses of aviation authority radars which might incorporate on the way radar frameworks, air observation radar (asr) frameworks, accuracy approach radar (standard) frameworks, and surface development radars [6,7].

1. En-Route Radar systems

The en-Route Radar is a special type of air traffic control (ATC) radar planned and created for on the way control of airspace. This sort of radar can be utilized to screen air traffic outside the extraordinary control regions close to landing strips. These sorts of radars ordinarily work in the L-band with a most extreme scope of up to 450 km. They are essential radars, which ordinarily give a two-layered perspective on the airspace. Normally, these radars coupled all of the time with an advanced optional radar, which then, at that point, gives the third spatial direction. The radio wire of these essential radars are allegorical reflectors and sweep the airspace with a cosecant squared shape design. Seldom a planar cluster receiving wire is additionally utilized. Receiving wires pivot generally leisurely at a speed of 4 to 6 rpm (cycles each moment). A defensive radome might be introduced to cover the radio wires in ominous climatic conditions [7,8].

2. Air Surveillance Radar (ASR)

The Airport Surveillance Radar (ASR) is a methodology control radar used to distinguish and show the place of an airplane in the terminal region. These kinds of radar sets work for the most part in E-Band (2 to 3GHz) and are prepared to do dependably identifying and following airplane at heights under 7620 meters and ranges inside 75 to 110 km of their air terminal. The pivot of the ASR turns quicker at 12 to 15 rpm (cycles each moment). A defensive radome might be introduced to cover the radio wires in ominous climatic conditions [7,8].

3. Precision Approach Radar (PAR)

When an aircraft is to land in bad weather conditions, it needs a control mode. In this case, the pilot is guided by ground control using Precision Approach Radar (PAR). There are two ways to send the guidance information, namely, either the radar operator sending voice commands to the pilot or using a computer link to the aircraft. These radar sets operate usually in I-Band (8.0 to 10.0 GHz) [8,9].

4. Surface Movement Radar (SMR)

In bad climate, the Surface Movement Radar (SMR) examines the air terminal surface to find the places of airplane and ground vehicles and afterward shows them for air traffic regulators. Surface development radars work in I-K-Band (8.0 to 40 GHz) and utilize an extremely short heartbeat width to give a satisfactory reach goal. By and large, the reach is restricted to a couple of kilometers and the radio wire turn speed is 60 cycles each moment [8].

B. Detection of Signals in Noise [9,10]

The word noise in the radar system is denoted to the electromagnetic unwanted energy that interferes with the receiver ability to detect the desired signal, the following is the generated noise in the component of the system.

1. Radar Receiver Noise

The noise might enter the recipient through the antenna alongside the ideal transmission or it could be produced inside the collector. In normal activity, noise is produced by the thermal movement of the conduction electrons in the ohmic bits of the recipient input stages. This is known as Thermal or Johnson Noise. Clamor power PN is communicated as far as the temperature To of a matched resistor at the contribution of the collector [9].

\[ P_N = kT_\circ \text{ Watt} \quad \text{... (1)} \]

Where: \( k \) is Boltzmann’s Constant (\( 1.38 \times 10^{-23} \text{ J/K} \)), \( T_\circ \) is System Temperature (normally 290K), and \( \square \) is Receiver Noise Bandwidth (Hz), while the reciver output total noise \( N \) can be estimated to the output noise power from an ideal receiver multiplied by the Noise Figure (NF) factor.

\[ N = P_N F_N kT_\circ \text{NF Watt} \quad \text{... (2)} \]

2. Noise Probability Density Functions

A typical radar components can be an antenna and wideband amplifier, that converts the signal to IF intermediate frequency, which is also filtered and amplified (bandwidth \( \beta F \)).

This is followed by an envelope detector and further filtering (bandwidth \( \beta V = \beta F/2 \)).

A Gaussian noise (as it is thermal) is assumed entering the IF filter with a probability density function (PDF) given by [9]

\[ P(v) = 1/(\sqrt{2\pi \beta V}) \exp\left(-v^2/(2\beta V)\right) \quad \text{... (3)} \]

Where \( p(v) \) is the probability of finding the noise voltage level \( v \) between \( v \) and \( V+dv \), and \( \beta \) is the noise variance voltage.

3. Probability of False Alarm

The occurrence of a false alarm happens whenever the noise voltage exceeds a defined threshold voltage \( V_t \). The probability of this called probability of false alarm (Pfa) and determined from the PDF as follows [9]:

\[ \text{Prob}(V_t < R < \infty) = \frac{1}{(2\pi)^{\frac{1}{2}}} \int_{-\infty}^{\infty} e^{-x^2/2} \text{d}x = \frac{1}{(2\pi)^{\frac{1}{2}}} \text{erf}(R) \]

\[ = 1 - \text{erf}(R) = P_{fa} \text{ ... (4)} \]

The average time interval between crossing of the threshold is defined as the false alarm time \( T_{fa} \) and is given as below,

\[ T_{fa} = \lim_{N \to \infty} \frac{1}{N} \sum_{k=1}^{N} \left(T_k/T_{ave}\right) \text{ ... (5)} \]

Where, \( T_k \) is the time between crossings of the threshold \( V_t \) by noise envelope assuming the slope of the crossing is positive. The probability of the false alarm may be defined as the ratio of the time that the envelope is above the threshold to the total time as shown in figure (3) below.

\[ \text{P}_{fa} = \frac{1}{N} \sum_{k=1}^{N} \left(T_k/T_{ave}\right) = \frac{\sum_{k=1}^{N} T_k}{T_{ave}} \text{ ... (6)} \]

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Where the duration average of a noise pulse is taken as the bandwidth reciprocal of \( \frac{1}{T} \) and both \( t_k \) and \( T_k \) are defined and shown in figure (3).

**Figure (2):** False alarms by receiver output voltage due to noise.

For the case of having \( \theta = \theta_0 \cdot IF \), then the false alarm time can be written as:

\[
T_{fa} = \frac{1}{\beta_0 \cdot IF} \exp \left( \frac{V_t^2}{\omega_0} \right) \ldots (7)
\]

### C. Calculation of Time between false alarms for specific values of single pulse Signal/Noise Ratio (SNR1) with Mathcad.

The following Mathcad codes are used to calculate and plot the time between false alarm in hours and the probability of false alarm against SNR in dB. While figure (3) shows the time between false alarms (in hours) against SNR in dB, and figure (4) shows the probability of false alarm against SNR in dB

\[
T_{fa} (BW, SNR_{dB}) = \frac{1}{\beta_0 \cdot IF} \exp \left( \frac{V_t^2}{\omega_0} \right) \ldots (8)
\]

\[
SNR_{dB} = 9, 9.05..20 \ldots (9)
\]

\[
T_{fa} (BW, SNR_{dB}) = \frac{T_{fa} (BW, SNR_{dB})}{3600} \ldots (10)
\]

**Figure (3):** Time between false alarms (in hours) against SNR in dB (SNRdB = VT2/\( \omega_0 \))

**Figure (4):** Probability of false alarm against SNR in dB (SNRdB = VT2/\( \omega_0 \))

### D. Probability of Detection [9]

It is assumed that an amplitude of a sine wave of A is given at the input stage with the noise of the IF filter. It is also assumed that the both frequencies of this sine wave and IF filter are equal. Rice [10] showed the envelope detector signal output will follow (Rician Distribution).

\[
Ps(R)=\frac{R}{\omega_0} \exp\left(-\frac{(R^2+A^2)}{2\omega_0}\right) \ldots (11)
\]

Where, \( I_0(Z) \) is the modified Bessel function of zero order. It is shown that the probability of detection \( P_d \), is the same as the probability that the envelope \( R \) will exceed the threshold \( V_t \) and may be given as:

\[
P_D = \frac{\sqrt{\ln(1/P_{fa})}}{\sqrt{(2\omega_0^2 + A^2/2\ln(1/P_{fa}))}} Q \ldots (12)
\]

\[
Q(\alpha, \beta) = \int_{-\infty}^{\alpha} \frac{e^{-x^2/2}}{\sqrt{\pi}} \, dx \ldots (13)
\]

It seems that the above equation is very complicated and takes time and one can use Empirical equation with good accuracy as follows:

\[
P_D = 0.5xerfc(-\ln(P_{fa}) - \sqrt{(SNR+0.5)}) \ldots (14)
\]

**Mathcad Codes to calculate Eq. (5.3).**

\[
P_d (SNR_{dB}, P_{fa}) = \text{erfc}(-\ln(P_{fa}) - \sqrt{(10\ln(SNR_{dB}/10)+0.5)}) \ldots (15)
\]

\[
SNR_{dB} = 1, 1.1..20
\]

As the plot of \( P_d \) versus \( SNR_{dB} \) is shown in Figure (6).
Figure (5): Probability of detection versus SNR1dB.

E. Calculation of SNR1 as function of Pfa and Pd Using Albersheim Empirical Formula.

\[ \text{SNR1}(Pd,Pfa) := A(Pfa) + 0.12A(Pfa)B(Pd) + 1.7B(Pd) \]  \hspace{1cm} (16)

Where

\[ A(Pfa) := \ln (0.62/Pfa) \]  \hspace{1cm} (17)

\[ B(Pd) := \ln (Pd/(1-Pd)) \]  \hspace{1cm} (18)

\[ \text{SNR1}_{dB}(Pd,Pfa) := 10 \log (\text{SNR1}(Pd,Pfa)) \]  \hspace{1cm} (19)

Table (1) given below shows calculations (using Mathcad) of SNR1dB for various values of Pd and Pfa.

Table (1): SNR1dB with Pd and Pfa.

<table>
<thead>
<tr>
<th>Pd</th>
<th>Pfa</th>
<th>SNR1dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>1.37</td>
</tr>
<tr>
<td>2</td>
<td>0.02</td>
<td>1.95</td>
</tr>
<tr>
<td>3</td>
<td>0.03</td>
<td>2.37</td>
</tr>
<tr>
<td>5</td>
<td>0.05</td>
<td>3.17</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>4.17</td>
</tr>
</tbody>
</table>

IV. Target Detection Loss (LdB) [9,17]

Detection loss may be calculated using empirical formula as shown below:

\[ C_x(1) = (\text{SNR1}) - 2.3)/\text{SNR1} \]  \hspace{1cm} (20)

Where the loss in SNR is \( C_x(1) \), and \( \text{SNR1} \) is the single pre detected pulse SNR to reach a specific values of Pd and Pfa. Mathcad code is shown in the following equations.

\[ L_{\text{det}}(\text{SNR1}) = (\text{SNR1}-2.3)/\text{SNR1} \]  \hspace{1cm} (21)

\[ L_{\text{dB}}_{\text{det}}(\text{SNR1}_{dB}) = -10 \log ((10^x(\text{SNR1}_{dB})/10)-2.3)/10^x(\text{SNR1}_{dB})/10) \]  \hspace{1cm} (22)

\[ \text{SNR1}_{dB} = 0, 1.01..20 \]  \hspace{1cm} (23)

A Mathcad code to calculate detection loss in dB versus probability of detection for different values of probability of false alarm (Pfa) is shown in the following equations.

\[ DL_{dB}(Pdd,Pfaa) = LdB_{det}(\text{SNR1}_{dB}(Pdd,Pfaa)) \]  \hspace{1cm} (24)

\[ DL_{i} = DL_{dB}(Pdi,10^{i}(-6)) \]  \hspace{1cm} (25)

A plot showing target detection loss versus Pd and Pfa is shown in figure (6). It is noted that this kind of loss is considered very small compared with other losses.

Figure (6): Detection loss against Pd for various values of Pfa.

Matched Filter Design [13,14,16]

The SNR can accomplish its greatest worth when the IF channel is matched to the kind of the sign at the contribution of the channel. The proportion of the pinnacle sign to average commotion force of the result reaction of the corresponding channel is equivalent to two times the got energy signal E isolated by the single-sided clamor power per Hz, No.

\[ (S/N)_{out} = 2E/N_0 \]  \hspace{1cm} (28)

Where, \( S \) is the peak instantaneous signal seen during the matched filter response to a pulse (in Watt), N is the average noise power (in Watt), E is the received signal Energy (in Joule) and No is the single-sided noise power density (in Watt/Hz).

At the point when the transfer speed of the sign at IF is smaller contrasted with the middle recurrence, then, at that point, the pinnacle power is roughly equivalent two times the normal power in the beneficiary heartbeat. It’s shown that:

\[ (S/N)_{out} = (S/N)_{in} \times BT \]  \hspace{1cm} (29)

Compared to Matched filter (in dB) the loss in SNR is tabulated in Table (2) below.

Table (2): Loss in SNR (in dB) compared to Matched Filter

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>Filter</th>
<th>Optimum B. t</th>
<th>Loss in SNR compared to Matched Filter dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular Pulse</td>
<td>Rectangular</td>
<td>1.37</td>
<td>0.85</td>
</tr>
<tr>
<td>Rectangular Pulse</td>
<td>Gaussian</td>
<td>0.72</td>
<td>0.49</td>
</tr>
<tr>
<td>Gaussian Pulse</td>
<td>Rectangular</td>
<td>0.72</td>
<td>0.39</td>
</tr>
<tr>
<td>Gaussian Pulse</td>
<td>Gaussian</td>
<td>0.44</td>
<td>0 (matched)</td>
</tr>
<tr>
<td>Rectangular Pulse</td>
<td>Single tuned</td>
<td>0.4</td>
<td>0.83</td>
</tr>
<tr>
<td>Rectangular Pulse</td>
<td>Two cascaded tuned circuits</td>
<td>0.613</td>
<td>0.56</td>
</tr>
<tr>
<td>Rectangular Pulse</td>
<td>Five cascaded tuned circuits</td>
<td>0.672</td>
<td>0.5</td>
</tr>
</tbody>
</table>

L_{MF} (MF) := [((1.37@0.85))if MF="RPR" @((0.72@0.49))if MF="RPG" @((0.72@0.39))if MF="GPR" @((0.44@0))if
MF="GPG"@(■(0.4@0.88))if MF="RP1CT"@(■(0.613@0.56))if MF="RP2CT"@(■(0.672@0.5))if MF="RP5CT")┤ … (30)

Where, (RPR) is Rectangular Pulse Rectangular Filters, (RPG) is Rectangular Pulse Gaussian Filters, (GPR) is Rectangular Pulse Rectangular Filters, (GPG) is Gaussian Pulse Gaussian Filters, (RP1CT) is Rectangular Pulse Single Tuned Circuit Filters, (RP2CT) is Rectangular Pulse 2 Cascaded Tuned Circuit Filters, and (RP5CT) is Rectangular Pulse 5 Cascaded Tuned Circuit Filters.

Integration of Returned (echo) Pulses [5,6,9]

As far as search radars are concerned, it will scan previous targets and will continue in the beam until more than pulse is detected to successfu...
Performance of Typical ATC Radar Using Mathcad

This section will show the procedure and steps of calculating the maximum range in km of a typical ATC radar. The radar range equation adopted is given as:

\[
R_{\text{max}} = \sqrt[4]{\frac{(P_t \cdot G \cdot A_e \cdot e_i(n))}{(4\pi)^2 \cdot K \cdot T_\circ \cdot BW \cdot F_n \cdot \text{SNR}(1) \cdot \text{Total Loss}}} \text{ meters} \quad (39)
\]

Where, \(P_t\) is Peak (pulse) transmitted radar power (watt), \(G\) is Gain of the radar antenna, \(A_e\) is The effective aperture of the antenna (m²), \(e_i(n)\) is The target radar cross-section area (m²), \(n\) is Number of integrated Pulses, \(E_i(n)\) is Integration Efficiency, \(k\) is Boltzmann Constant = \(1.38\times10^{-23}\) Joules/Kelven, \(T_\circ\) is Equivalent noise temperature (in Kelven), \(BW\) is Receiver bandwidth (in Hertz), \(F_n\) is Receiver noise figure, \(\text{SNR}(1)\) is Signal to Noise power ration one pulse, and \(\text{Total Loss}\) is Total Losses.

Equation (6.1) include SNR which is a random quantity since it depends on noise (random event) and this depend on probability of detecting a target \(P_d\) and probability of false alarm \(P_{fa}\). Therefore, the calculation of the maximum range of the target will be expressed as function of \(P_d\) and \(P_{fa}\). Equation (6.1) shows that total losses is considered one of major parameter that affect the target range calculation.

The Performance of ATC Radar.

In Mathcad one can use data table that will take the values as input data and this is shown in table 3.

**Table (3): Mathcad Code For a typical ATC Radar Parameter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_t)</td>
<td></td>
</tr>
<tr>
<td>(G)</td>
<td></td>
</tr>
<tr>
<td>(A_e)</td>
<td></td>
</tr>
<tr>
<td>(e_i(n))</td>
<td></td>
</tr>
<tr>
<td>(n)</td>
<td></td>
</tr>
<tr>
<td>(E_i(n))</td>
<td></td>
</tr>
<tr>
<td>(k)</td>
<td></td>
</tr>
<tr>
<td>(T_\circ)</td>
<td></td>
</tr>
<tr>
<td>(BW)</td>
<td></td>
</tr>
<tr>
<td>(F_n)</td>
<td></td>
</tr>
<tr>
<td>(\text{SNR}(1))</td>
<td></td>
</tr>
</tbody>
</table>

Total Loss Calculations for a typical ATC radar [8,]

The following equations shows the Mathcad code which is used in the calculating the total loss in dB for a typical ATC radar.

**Basic Losses (dB)**

\[
\text{ScanLoss}_dB = 1.6 \\
\text{LossMF}_dB = 0.56 \\
NF_dB = 4 \\
\text{AntΩ}_L = 0 \\
\text{TLx}_L = 2 \\
\text{TLr}_L = 2 \\
\text{AntPatt}_L = 1.6 \\
\text{Misc}_L = 2
\]

**BasicLoss_dB =** \(\text{ScanLoss}_dB + \text{LossMF}_dB + NF_dB + \text{AntΩ}_L + \text{TLx}_L + \text{TLr}_L + \text{AntPatt}_L + \text{Misc}_L + \text{BasicLoss}_dB\) \(dB = 13.76 \quad (40)\)

**Integration Loss (dB)**

\[
\text{IntegLoss}_dB = [\text{Li}_dB (NPulse,Pd,P_{fa})] \quad (41)
\]

**Loss MF dB** = 0.56

**IntegLoss_dB =** \(1.225 \quad (42)\)

**AddLoss_dB =** \(\text{IntegLoss}_dB + \text{Loss MF}_dB \quad (43)\)

**Total Loss**

\[
\text{TotalLoss}_dB = \text{BasicLoss}_dB + \text{AddLoss}_dB \quad (44)
\]

VI. Results & Analysis

In this paper a mathematical model for ATC radar is build using Mathcad software. The Mathcad model is applied to a typical ATC radar whose parameter are given in Table(3) Results of this Mathcad model are given in figures (9 to 12). Results shown in figure (9), the effect of fluctuating targets on the maximum radar of ATC radar for range of probability of target detection. The effect of the number of integrated pulses are shown in figures (10 and 11) for different values of probability of detection. The Mathcad model is also tested to show the effect probability of false alarm as shown in figure (12). These results are considered very essential in evaluating ATC radars.
Figure (9) Maximum radar range versus % probability of detection.

Figure (10) Maximum radar range versus number of integrated pulses, with Pd =0.8.

Figure (11) Maximum radar range versus number of integrated pulses, with Pd =0.99.

Figure (12) Maximum radar range versus probability of false alarm, Pfa.

VII. Conclusions

In this paper, a mathematical model is built using Mathcad software for the ATC radar. The model is based on mathematical expressions used in radar engineering publications and on probabilistic formulas. The model requires basic information about the ATC radar and pass it to Mathcad instructions built in the model. The output of the ATC radar model is prepared to display set of plots. These plots are well prepared and give important information of maximum target range that the radar can reach for various parameters, such as, probability of target detection, probability of false alarm, number of integrated pulses and for stationary and fluctuating targets. The model built in this paper is capable to handle different types of ATC radars and present the results in various ways, such as tables as well as plots.

References


