國立中山大學 應用數學 學系(研究所)

碩士論文

題目: 基於統計模型做為開放測試場地下標準場地衰

減測量品質衡量之模擬研究

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摘要

當我們在測量一儀器或設備的電磁波強度時,一開放空間的 EMI 觀測值是最直接也是最常被接受的標準測量方式。如果在不同頻率所紀錄觀察到的電磁波測量值(NSA)沒超過理論值(ideal values)加減 4dB 的範圍的話，這個場地就被認定為一個合格的標準場地，否則只要有一個值超出範圍就是一個不合格的場地。在此之前，已有一些研究利用一個轉折點模型來配適觀測值。在本研究中，對於每一組觀測值和其相對應之理論值，我們分別配適一個轉折點模型，並根據所得到的迴歸參數估計值作比較。我們的目標是希望能探討觀測值與理論值間參數估計的差異，去判斷一個場地合格與否是否可行。所使用到的評估方法就是考慮觀測值所得之迴歸參數估計是否落在適當的信賴域中來做決定。最後，根據在四個不同測試場地所收集到的數據，分別利用本文中所提之統計方法配適統計模型，並進一步來比較四個測試場地的測量品質。

關鍵字： EMI，轉折點模型，信賴域。

A simulation study on quality assessment of the Normalized Site Attenuation (NSA) measurements for Open-Area Test Site using statistical models.

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Abstract

Open site measurement on the electromagnetic interference is the most direct and universally accepted standard approach for measuring radiated emissions from an equipment or the radiation susceptibility of a component or equipment. In general, if the NSA measurements we recorded at different frequencies do not exceed the ideal value $\pm 4dB$,we would regard this site as a normalized site, otherwise it is not a normalized site as long as there is one measurement exceeds the range. A one change point model had been used to fit observed measurements. For each set of observations as well as the corresponding ideal values, we have the estimated regression parameter for a one change point model. Our ideal is using the difference of regression parameters between ideal values and observations to assess whether a site is qualified for measuring EMI or not. The assessment tool for whether the testing site is normalized or not is referred to the confidence region for the regression model parameters. Finally, according to the data collected in this experiment, the estimated parameters obtained from the observations will be used to do further statistical analyses and comparing the qualities of the four different testing sites.

Keywords : EMI, Change point model, Confidence region.

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1 Introduction

The electromagnetic environment is an integral part of the world in which we live. Various apparatus such as radio and television broadcast stations, communication transmitters, and other radar and navigational aids radiate electromagnetic energy during their normal operation. These are intentional radiations of electromagnetic energy into the environment. Many appliances such as automobile ignition systems and industrial control equipment used in everyday life also emit electromagnetic energy, although these emissions are not an essential part of normal operation. Many other examples of unintentional radiators are ubiquitous. The electromagnetic environment created by these intentional and unintentional sources, when sufficiently strong, interferes with the operation of many electrical and electronics equipment and systems. Integrated circuits, which are today extensively used in many instruments of apparatus, including information technology products. Suffer the most from EMI. In extreme cases, EMI may cause burnout of such devices. In circuits involving digital signals, the effect of EMI could be one of increasing the bit error rates or malfunctioning of the circuit. In case of analog signals, EMI increases the noise levels and leads to a degraded operation of circuits and systems.

The above examples are not a comprehensive list of experiences in all fields. These are indicative of recent experience and concerns that serve as an illustration of the type of EMI problems that continue to be experienced. The object is not to raise an alarm but to point out that EMI/EMC is today a multidimensional problem, calling for constant attention in the design and practical use of all electrical and electronics apparatus and systems, particularly in communications and control.

Whether a site is qualified for testing EMI or not is decided by the antenna measurements. In Wang et al. (2004), a one change point model had been used to fit observed measurements and compared the difference with two kinds of antenna (broadband antenna and dipole antenna). Detecting the change point problem have been discussed by many authors, for example, Page (1954,1955,1957) used the nonparametric method (CUSUM) to give a one-sided test for a change in the mean of a distribution, Hudson (1966) and other authors use the maximum likelihood and least square methods etc to estimate the change points. In general, if the NSA measurements we recorded at different frequencies do not exceed the ideal value $\pm 4dB$,we would regard this site as a normalized site, otherwise it is not a normalized site. For all of our data, a one change point model will be established, and the estimated model parameters will be used to determine whether the testing site is normalized or not. In section 2, we give a description of the data sets and discuss briefly on comparisons of some relations between the repeated measurements. In section 3, we will introduce some statistical models and explain the research method and purpose in this work. In section 4, we will present some simulation results on the issues proposed to be studied in section 3 and infer which site is more suitable for antenna measurements. Finally, we will propose some problems worthy of further investigation in the future. Then we may make more precise inference on the quality for measuring EMI.

2 Data description

Open site measurement is the most direct and universally accepted standard approach for measuring radiated emissions from an equipment or the radiation susceptibility of a component or equipment. The basic principle of measurement (Equipment Under Test) testing radiated emissions is with the EUT switched on, the receiver is scanned over the specified frequency range to measure electromagnetic emissions from the EUT and determine the compliance of these data with the stipulated specifications. With the help of a proper test site and a calibrated receiving antenna, radiated emissions from equipment under test over a specified frequency band can be measured observing various precautions. Similarly, using a calibrated transmitting antenna, susceptibility of equipment under test can be checked under specified field conditions. If these measurements are done in a room, or an enclosed area, it is possible that reflections or scattered signals from walls, floor, and ceiling will be present. The presence of such scattered signals will corrupt the measurements. However, if these measurements are done in a proper open-area test site, the scattered signals and reflections will not be present. In this work, all of our data are from open-area test work, where different test setups in these experiments are listed below.

Table 1. The different setups of experiments

factor	level	explanation
site	metal screen	metal screen upon the ground
	metal plane	metal plane upon the ground
antenna	bb	broadband antenna
	dp	dipole antenna
polarization of antenna	hor	horizontal
	ver	vertical
h1	1m,1.5m,2m,2.75m	transmit antenna height
h2	1-4m,2.75-4m	receive antenna height
R	10m	antenna separation relative to ground plane

At every setup, measurements from frequency 30MHz to 1000MHz are recorded, the sample size is 27 and experiments at each setup are repeated for 3 times. The detailed lists about our data is given in Table 2. For the four test sites, the site with metal screen upon the ground for our data are OATS A and OATS D, but with the metal plane upon the ground are OATS B and OATS C. We will discuss whether the metal plane is better than the metal screen later.

Table 2. The four test sites of data for this experiments

setup for experiment	OATS A	OATS B	OATS C	OATS D
broabband, hor, h1=1m, h2=1-4m, R=10m	screen	plane	<u>plane</u>	screen
broabband, hor, h1=2m, h2=1-4m, R=10m	screen	plane	plane	screen
broabband, ver, h1=1m, h2=1-4m, R=10m	<u>screen</u>	<u>plane</u>	<u>plane</u>	screen
broabband, ver, h1=1.5m, h2=1-4m, R=10m	<u>screen</u>	plane	plane	screen
dipole, hor, h1=2m, h2=1-4m, R=10m	screen	plane		
dipole, ver, h1=2.75m, h2=2.75-4m, R=10m	screen	plane		

(_:The NSA measurements we recorded at some frequencies exceed ideal values $\pm 4dB$)

Note that according to Akria (1990,1992) the theoretical formula of NSA's values and E_D^{MAX} can be expressed as

$NSA_{TH} = -20log(f_M) + 48.9 - E_D^{MAX}$,

where f_M= frequency in MHz, E_D^{MAX}= maximun received field, and the formula of E_D^{MAX}(vertical and horizontal) is

$$E_{DH}^{MAX} = \frac{\sqrt{49.2}(d_2^2 + d_1^2|\rho_H|^2 + 2d_1d_2|\rho_H|\cos[\Phi_H - \frac{2\pi}{\lambda}(d_2 - d_1)])^{1/2}}{d_1d_2},$$

$$E_{DV}^{MAX} = \frac{\sqrt{49.2}R^2(d_2^6 + d_1^6|\rho_V|^2 + 2d_1^3d_2^3|\rho_V|\cos[\Phi_V - \frac{2\pi}{\lambda}(d_2 - d_1)])^{1/2}}{d_1^3d_2^3},$$
$$E_D^{MAX}(ideal) = 48.9 - 20log(f_M) - ideal.$$

details of E_{DH}^{MAX} we listed in the Appendix. We first draw scatter plots with measurement versus frequency (Figure A.1) and measurement versus log(freq) (Figure A.2) respectively in order to find some information about these setups of data. While observing the scatter plots, it can be seen that the graph fluctuates more when the frequency is lower than 200MHz. Except the OATS A, it is easy to see that all repeated measurements are very close because they measure the observations three times at the same day, but in OATS A they measure the observations three times at different days. We use the Friedman Test presented in the Appendix to do the comparisons. By using the Friedman test to test the repeated measurements in OATS A (Table A.1), the repeated measurements have significant differences in setup with broadband antenna, horizontal, h1=1m, h2=1-4m. In the remaining three sites, they do not seem to have differences between the repeated measurements because the repeated measurements are all very close. A one change point model is fitted for each set of data and the results of measuring SSE respectively are listed in Table A.6 in the Appendix. In the OATS A, the NSA measurements fluctuate more than the data in the other three sites, and the same situation occurred for the SSE. Even though the repeated measurements have some differences in OATS A, but we can see that trends are quite similar at three different days and the regression parameter β fitted are very close. So if the repeated measurements come from the same day, then the difference of them may be very tiny. But when we measure the observations at different days, then there may be some systematic differences. This is because that the weather changing may affect the NSA measurements.

3 Statistical models and Analysis

For each set of observations, we have the estimated regression parameter for one change point model. Once we obtained the estimated parameter from the observations, we are interested in whether the estimated parameter $\hat{\beta}$ comes from a normalized test site or not.

In order to know whether we can use the difference of the estimated regression parameter between ideal values and observations to assess a test site is normalized or not, we have proposed a new method as follows. After using one change point model fitted to observations, we use the confidence region method to assess the quality of the estimated parameter $\hat{\beta}$. The goal of the section is to determine the critical value under the confidence region method to judge whether the test site is normalized or not. In the end of this section, simulation method and some behaviors between the estimated parameters for the observed measurements of the EMI will also be discussed.

3.1 statistical models

3.1.1 one change point model

After introducing the data obtained in this experiment, we analyze the data by using statistical method. Following that of Wang et al. (2004), we firstly use a one change point model to fit data which is expressed as following

$$y_t = \beta_0 + \beta_1 t + \beta_2 (t - t_m) I_{[t>t_m]} + \varepsilon_t \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where y_t = measurement, $t = \log_{10}(\text{freq})$, $t_m = \log_{10}(\text{change point})$

$$I_{[t>t_m]} = \begin{cases} 0 & \text{if} \quad t \leq t_m \\ 1 & \text{if} \quad t > t_m \end{cases}$$

and the errors are assumed to be normally and independently distributed with constant variance σ^2. In matrix notation, the model given by (1) is

$$Y = X\beta + \varepsilon$$

where

$$Y = (\, y_1, \quad y_2, \quad \cdots, \quad y_{27}\,)^T, \quad X = (\, 1_{27}, \quad X_1, \quad X_2\,),$$

$$X_1 = (\, t_1, \quad t_2, \quad \cdots, \quad t_{27}\,)^T, \quad X_2 = (\, 0_m^T, \quad t_{m+1} - t_m, \quad \cdots, \quad t_{27} - t_m\,)^T,$$

$$\beta = (\, \beta_0, \quad \beta_1, \quad \beta_2\,)^T, \quad \varepsilon = (\, \varepsilon_1, \quad \varepsilon_2, \quad \cdots, \quad \varepsilon_{27}\,)^T,$$

with ε distributed as $N(0, \sigma^2 I)$. In general, Y is an 27×1 vector of the observations, X is an 27×3 matrix of the levels of the regressor variables, β is an 3×1 vector of the unknown regression coefficients, and ε is an 27×1 vector of random errors. The unbiased estimator of β and the corresponding SSE can be expressed as

$$\hat{\beta} = (X'X)^{-1}X'Y, \quad SSE = Y'Y - \hat{\beta}'X'Y.$$

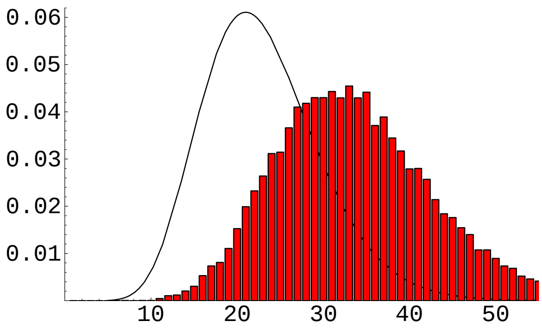
Both $\hat{\beta}$ and SSE may be different when we use models with different change point position to fit the observations. So we choose the point which makes the SSE of the fitted models the smallest as the estimated change point position, and we denote the estimated change point position as $\hat{t}_m$. We use one change point model to approximate the ideal values and the results are listed in Table 3. By Table 3, we can see that the estimated MSE is small for each ideal value data set and all have the $R^2 > 0.99$. We denote the estimated parameter for ideal values as $\hat{\beta}_T$, and the estimated parameters $\hat{\beta}_T$ for the ideal values have been listed in Table 3. The results for using one change point model fitted to observations in four test sites are also quite well (see Table A.2, A.3, A.4, A.5).

Table 3. Results of using one change point model to fit the ideal values

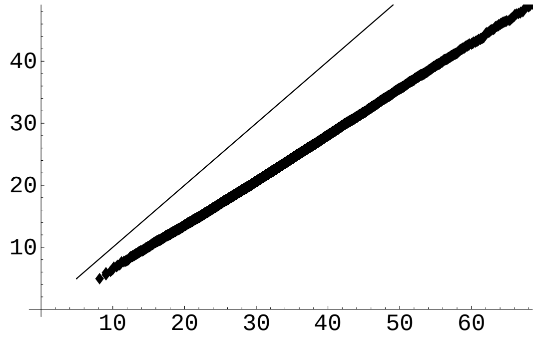
	cp(m)	regression line	MSE
bb,hor,h1=1m	150MHz(14)	$y = 84.712 - 37.3901t + 16.266(t - t_m)I_{[t>t_m]}$	0.0605
bb,hor,h1=2m	80MHz(8)	$y = 77.164 - 36.001t + 15.467(t - t_m)I_{[t>t_m]}$	0.0308
bb,ver,h1=1m	400MHz(21)	$y = 43.754 - 18.555t - 4.463(t - t_m)I_{[t>t_m]}$	0.0669
bb,ver,h1=1.5m	250MHz(19)	$y = 43.093 - 18.014t - 4.728(t - t_m)I_{[t>t_m]}$	0.0638
dp,hor,h1=2m	80MHz(8)	$y = 77.164 - 36.010t + 15.469(t - t_m)I_{[t>t_m]}$	0.0308
dp,ver,h1=2.75m	120MHz(11)	$y = 47.714 - 19.679t - 2.084(t - t_m)I_{[t>t_m]}$	0.1056

The summary of using one change point model fitted to EMI data is listed in the Table A.7 in the Appendix, it shows that the change point position is not always the same. When the polarization for antenna is horizontal, we can see that the estimated change point positions are very close. But the estimated change point positions fluctuate more when the polarization for antenna is vertical. It is of interest to know what may be the pattern of the change point position. In order to know the pattern of the change point position, we have done some simulation by given the ideal values as the mean under each frequency as well as by given the estimated expected values from the one change model as the mean under each frequency, and the results of simulation are listed in Figure A.4 in the Appendix, where we can see that if the given value of σ in the simulation is small, then the change point position will be closer to the change point position of ideal values (listed in Table 3). This phenomenon will be conformed to the results of our data, especially when the polarization of antenna is horizontal.

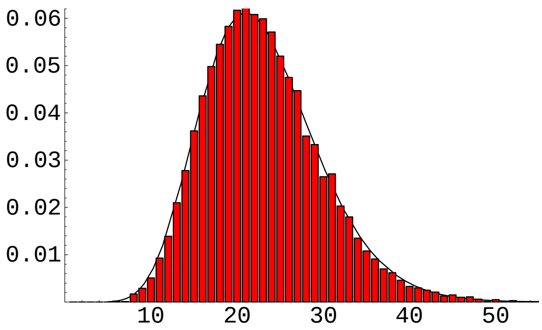
In order to know whether the degree of freedom associated with MSE we chose as 23 is suitable or not, for each set of data, we can use one change point model fitted to data and obtain the estimation of SSE. Once we obtain 100,000 times value of $\frac{SSE}{\sigma^2}$ from simulation, then we can use them to draw the Barchart plot and Quantile-Quantile plot, compare the Barchart plot and Quantile-Quantile plot with the *pdf* of χ^2_{23} distribution. Result of using σ equals 0.5 to simulate data has been listed in Figure 1. From the result listed below, we can see that the approximation will become very bad when we use $\mu = T$ to do the simulation. On the other hand, the result for using $\mu = \hat{Y}_T$ to do the simulation can be approximated quite well by χ^2_{23} distribution. This phenomenon seems to indicate that the approximated result for using $\mu = T$ to do the simulation will become very bad when the given value of σ in the simulation is small. We guess this phenomenon is caused by the following factor. That is, $\hat{Y}_T$ is obtained from a one change model, so the approximated result for the SSE seems to fit quite well under a suitable model assumption. But when we use $\mu = T$ to simulate data, the bad approximation occurred because there are differences between the ideal values and that from the one change point model. This indicates that the ideal values may be approximated by a one change point model, but there are still some differences especially when the value of σ is small, then the issue of bias during the modeling process may be more seriously reflected in the SSE, therefore the approximation of SSE through the χ^2_{23} distribution may turn out to be inappropriate. But when the value of σ in the simulation is not that small, then the approximation for SSE through the χ^2_{23} distribution does not seem to be too bad. In the following, we use both ideal values and fitted values of the ideal values as the mean vector to generate data and investigate under what conditions, the results for using two methods may be comparable by simulation in next section.



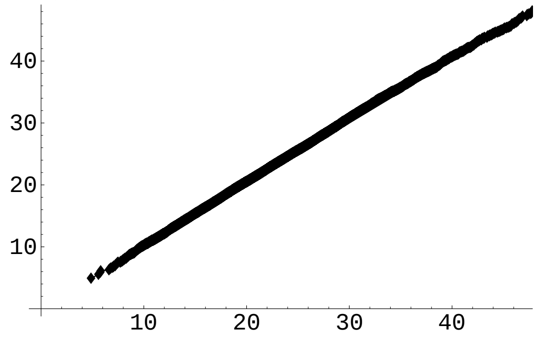
(a)Barchart($\mu = T$ and $\sigma = 0.5$)



(b)Q-Q Plot($\mu = T$ and $\sigma = 0.5$)



(c)Barchart($\mu = \hat{Y}_T$ and $\sigma = 0.5$)



(d)Q-Q Plot($\mu = \hat{Y}_T$ and $\sigma = 0.5$)

Figure 1. Plots of the value of the SSE/σ^2 in the setup with Dipole antenna, ver, h1=2.75m, h2=2.75-4m

3.1.2 Confidence region for regression parameter

Consider the one change point model with give change point position, the regression parameter β is a 3×1 vector and the sample size for measurements in setup is 27. Then joint confidence region for all 3 parameters in β is obtained from the inequality

$$\frac{(\hat{\beta} - \beta)'(X'X)(\hat{\beta} - \beta)}{3\ MSE} \sim F_{3,v}$$

where v is the degrees of freedom associated with MSE. It should be mentioned that the X matrix is not the same in each setup as the change point position may not be the same. Although if the change point position is fixed in advance, then the degree of freedom for v will become 24. When $\hat{\beta}$ and MSE are estimated using the matrix X with the same change point position of ideal values. Then this implies that

$$P\left(\frac{(\hat{\beta} - \beta)'(X'X)(\hat{\beta} - \beta)}{3\ MSE} \leq F_{\alpha,3,24}\right) = 1 - \alpha$$

Consequently, a $(1-\alpha)100\%$ joint confidence region for all of the parameters in β is

$$\frac{(\hat{\beta}-\beta)'(X'X)(\hat{\beta}-\beta)}{3\ MSE} \leq F_{\alpha,3,24}$$

But in the real data analysis, the change point position may not be the same. For example in the setup with broadband antenna, hor, h1=2m, h2=1-4m, the change point position of ideal values is approximated to be at the frequency 80, but the change point position for our real data is estimated to be at frequency 70. On the other hand, from Table A.8 listed in Appendix, based on the one change point model, there are some differences for the estimated parameter $\tilde{\beta}_{T_m}$ of ideal values at different change point frequencies. Therefore, it is not reasonable to compare the estimated parameter vector based on ideal values and the one with the observations, as their best change point position estimates are different. So we will make some revision to the definition of the confidence through the total probability of confidence region conditioning on the change point position. That is to compute confidence by conditioning on the same change point position for both observed and ideal values and make the comparisons between the estimated parameter vectors:

$$\sum_{m=2}^{26} P\left(\frac{(\hat{\beta}_m-\tilde{\beta}_{T_m})'(X_m'X_m)(\hat{\beta}_m-\tilde{\beta}_{T_m})}{3\ MSE_m} \leq F_{\alpha,3,23}|CP=m\right) P(CP=m)$$

where X_m is the matrix X with the m-th change point position, $(\hat{\beta}_m, MSE_m)$ is the estimation coming from the observed values by using the matrix X_m to fit one change point model, and $\tilde{\beta}_{T_m}$ is the estimation coming from the ideal values by using the same matrix X_m. Since the change point position will not occur in the lowest frequency and the highest frequency, so the change point position estimates must be restricted to the interval between the second lowest frequency and second highest frequency. In this case, the degree of freedom for MSE_m is revised to be 23, as one degree of freedom has been used for the estimation of the change point position.

3.2 Simulation procedure

In this subsection, we firstly use two methods to generate data. By using the simulation data to fit one change point model, then we will use these estimated parameters to do further analyses. Two kinds of data generated are based on joint normal distribution with (i) mean vector $\mu = T$ and covariance matrix $\sum = \sigma^2 I$, (ii) mean vector $\mu = \hat{Y}_{T}$ and covariance matrix $\sum = \sigma^2 I$, where T is the 27×1 vector with ideal values at 27 frequencies and $\hat{Y}_{T}$ is the fitted value with one change point model for the ideal values. In the actual situation, since the ideal values are used to assess whether a site is qualified for measuring or not, we will state the procedure for using $\mu = T$ and a given σ to generate data, and the procedure for the case with $\mu = \hat{Y}_{T}$ to generate data is similar. Now we assume that observations at different frequencies are independent and $Y \sim N_{27}(T, \sigma^2 I)$, with given σ, then there are two types of probability of interset, namely p_1 and p_2 are

$$p_1 = P\left(\frac{|y_1 - T_1|}{\sigma} \le \frac{4}{\sigma}, \frac{|y_2 - T_2|}{\sigma} \le \frac{4}{\sigma}, ..., \frac{|y_{27} - T_{27}|}{\sigma} \le \frac{4}{\sigma}\right) = (2\Phi(\frac{4}{\sigma}) - 1)^{27},$$

$$p_2 = \sum_{m=2}^{26} P\left(\frac{(\hat{\beta_m} - \tilde{\beta}_{T_m})'(X_m' X_m)(\hat{\beta_m} - \tilde{\beta}_{T_m})}{3\ MSE_m} \le F_{\alpha,3,23} | CP = i\right) P(CP = m).$$

Note that p_1 represents the probability of the site passing the $\pm 4dB$ requirements for measuring EMI for given σ, and p_2 represents the probability that the estimated parameter falls into the confidence region by the conditional method. The probability that the site is qualified for measuring EMI and falls into the confidence region by the conditional method is also discussed in the following, and we define it as p_3. The direct meaning of p_3 is that we can use adjusted confidence region method to judge whether the site is qualified for measuring EMI, which is:

$$p_3 = \sum_{m=2}^{26} P(\frac{(\hat{\beta}_m - \tilde{\beta}_{T_m})'(X_m' X_m)(\hat{\beta}_m - \tilde{\beta}_{T_m})}{3\ MSE_m} \le F_{\alpha,3,23}, |Y - T| \le 4 | CP = i) P(CP = m),$$

$$p_{21} = \sum_{m=2}^{26} P(\frac{(\hat{\beta}_m - \tilde{\beta}_{T_m})'(X_m' X_m)(\hat{\beta}_m - \tilde{\beta}_{T_m})}{3\ MSE_m} \le F_{\alpha,3,23}, |Y - T| \nleq 4 | CP = i) P(CP = m).$$

On the other hand, p_{21} represents the probability that the NSA measurements we recorded at some frequencies exceed ideal values $\pm 4dB$ and falls into the confidence region by the conditional method.

The simulation procedure is illustrated as follows. Firstly, we generate 1000 sets of observations, then we make some classification for our data to judge whether each set with 27 observations conform the ideal values $\pm 4dB$ or not, and obtained the estimated probability for p_1, say $\hat{p}_1$. Secondly, we determine whether or not these observed data yield statistical value to be smaller than the critical value under the adjusted confidence region method. Then two kinds of the estimated probabilities are given, say $\hat{p}_3$ and $\hat{p}_{21}$. The probability p_2 is the sum of two kinds of probability of p_3 and p_{21}. Repeat this procedure 100 times, and obtain the results of the estimated probabilities with 1000 data sets and simulation error of the estimated probability 100 times. The simulation procedure is illustrated below.

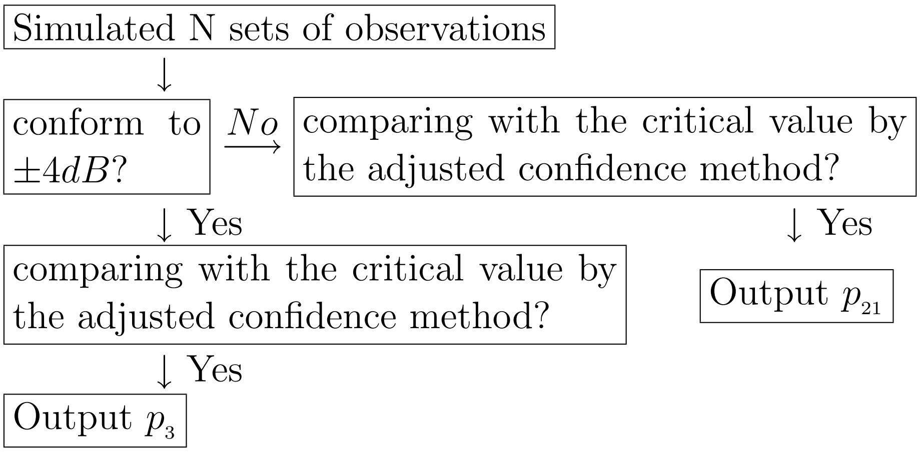


Figure 2. Simulation procedure

3.3 Quality assessment method

Under the one change point model, we have the estimated change point position $\hat{t}_m$ and the corresponding estimated parameter $\hat{\beta}_m$ from the observations. Later based on the change point model with the same change point position $\hat{t}_m$ to fit ideal values, we compare it with the corresponding estimated parameter $\tilde{\beta}_{T_m}$ from ideal values. Now we consider the total squared variation between fitted values of observations and fitted value of the ideal values with change point position at m-th position, the value can be expressed as

$$SS_{fitted_m} = \sum_{i=1}^{27} (\hat{y}_{mi} - \tilde{y}_{T_{mi}})^2 = (\hat{Y}_m - \tilde{Y}_{T_m})'(\hat{Y}_m - \tilde{Y}_{T_m}) = (\hat{\beta}_m - \tilde{\beta}_{T_m})'(X_m' X_m)(\hat{\beta}_m - \tilde{\beta}_{T_m}).$$

Furthermore, the corresponding MSE_m can be expressed as

$$V_{cr_m} = \frac{(\hat{\beta}_m - \tilde{\beta}_{T_m})'(X_m' X_m)(\hat{\beta}_m - \tilde{\beta}_{T_m})}{3MSE_m} = \frac{SS_{fitted_m}}{3MSE_m}.$$

If we can use a single value as the assessment criterion to compare the fitted situation for the estimated parameter $\hat{\beta}_m$ at different sites, then it is more convenient. The value of SS_{fitted_m} represents whether the estimated parameter $\hat{\beta}_m$ of observations is close to the estimated parameter $\tilde{\beta}_{T_m}$ of the ideal values or not. If the value of SS_{fitted_m} obtained from the observations is small, it implies that the fitted values of observations are close to the fitted values of the ideal values and the estimated parameter of observations is good. Once the value of SS_{fitted_m} obtained from the observations is large which implies that the estimated parameter $\hat{\beta}_m$ we fitted from the observations is not good and the quality of the test site is problematic. In order to assess the quality of the test sites, we list the value of SS_{fitted_m} in every setup in next section.

3.4 Pattern of the estimated parameter

Based on former experiences, while fitting a one change model for the observations, the second straight line for regression will be closer to the theoretical model with $48.9 - 20log_{10}(t)$. Once the intercept and slope of the second straight line obtained from the observations are away from the theoretical values, then the quality of the measurements should be queried. Those setups with measurements exceed ideal values $\pm 4dB$, the intercept and slope of the second straight line seem to have larger differences than the others, see Table A.7 in the Appendix for more details.

From the results listed in the Appendix, we can see that if the estimated $\hat{\beta}_{m0}$ from the observations is smaller than the the estimated $\tilde{\beta}_{T_{m0}}$ from the ideal values, then the estimated $\hat{\beta}_{m1}$ from the observations will usually be larger than the estimated $\tilde{\beta}_{T_{m1}}$ from the ideal values. This seems to indicate that the different trends exist in $\hat{\beta}_{m0}$ and $\hat{\beta}_{m1}$ for observations. That is, while observing that the estimated $\hat{\beta}_{m0}$ from the observations is different from the estimated $\tilde{\beta}_{T_{m0}}$, then calibration on the measurements would be so that the estimated $\hat{\beta}_{m1}$ may be adjusted in order to let the fitted situation for observations be closer to the ideal values $\pm 4dB$. For example, if we choose the change point positions at frequency 35 or frequency 900, then the corresponding matrix X^TX can be expressed respectively as

$$X_2^TX_2 = \begin{pmatrix} 27 & 59.61 & 17.99 \\ 59.61 & 137 & 45.05 \\ 17.99 & 45.05 & 17.27 \end{pmatrix}, X_{26}^TX_{26} = \begin{pmatrix} 27 & 59.61 & 0.05 \\ 59.61 & 137 & 0.14 \\ 0.05 & 0.14 & 0.01 \end{pmatrix}.$$

From the structure in the matrix X^TX, we see that if the the same trends exist in $\hat{\beta}_{m0}$ and $\hat{\beta}_{m1}$ for observations ($\hat{\beta}_{m0}$ and $\hat{\beta}_{m1}$ are all larger than $\tilde{\beta}_{T_{m0}}$ and $\tilde{\beta}_{T_{m1}}$), then the value of the SS_{fitted} will become very large. On the other hand, according to the definition of the matrix X listed in subsection 3.1, we will regard the term $\hat{\beta}_{m1}$ as the most significant effect for whether the fitted value of observations can conform the ideal values $\pm 4dB$ or not, and the same result will be obtained from the structure in matrix $X'X$. While revising the term in $\hat{\beta}_m$ for observations, we may easily find that the value of SS_{fitted} has the largest variation as the term $\hat{\beta}_{m1}$ away from $\tilde{\beta}_{T_{m1}}$. Or we can say that the term $\hat{\beta}_{m1}$ have the most significant effect than the other two terms in $\hat{\beta}_m$.

Based on different change point models fitted to the ideal values, we obtain the corresponding fitted values of the ideal values at different change point model. The maximum value of the absolute differences between the fitted values of the ideal values and ideal values can be expressed as

$$max\_bias_m = \max\{|\hat{y}_{T_{mi}} - T_i|; i = 1, 2, \cdots, 27, m = 2, \cdots, 26\}.$$

Based on the 25 possible change point models, the corresponding max_bias and the change position frequency will be recorded in Table A.9 in the Appendix. We find an interesting phenomenon when the polarization of antenna is vertical, the frequency that the max_bias occurs will be very close to the change point position of the ideal values. When the polarization of antenna is horizontal, the frequency that max_bias occurs either at the frequency that we chose as the change point model fitted to the ideal values or at the lowest frequency.

4 Results and Comparisons

In this section, we firstly perform simulations and discuss meticulously on the results of simulation. Then we compare the data collected in this experiment and infer which test site is more suitable for measuring EMI.

4.1 Simulation results

Now, we will discuss the simulation results. For clarity, the definition of the parameters listed in the following four Tables(from Table 5 to Table 8) is listed below.

Table 4. Definition of the estimated parameter

parameter	Definition
$\hat{p}_1$	the estimated probability that all 27 observations conform ideal values $\pm 4dB$
$\hat{p}_2$	the estimated probability that the value of V_{cr} is smaller than the critical value of adjusted confidence method
$\hat{p}_2^{'}$	the estimated probability that the value of V_{cr} is smaller than 7
$\hat{p}_3$	the estimated probability that conform ideal values $\pm 4dB$ and the value of V_{cr} is smaller than the critical value of adjusted confidence method
$\hat{p}_3^{'}$	the estimated probability that conform ideal values $\pm 4dB$ and the value of V_{cr} is smaller than 7
$\overline{MSE}$	the average of 100,000 times estimation of the MSE
SS^*_{fitted}	99% of the probability that the value of SS_{fitted} is smaller than the value given in the Table (SS_{fitted} comes from a normalized test site)

Table 5. Results of using $\mu = T$ and $\sigma = 1.123(\sigma^2 = 1.261)$ to generate observations.

$\mu = T$	bb,hor,h1=1m	bb,hor,h1=2m	bb,ver,h1=1m	bb,ver,h1=2m	dp,ver,h1=2.75m
p_1	0.99	0.99	0.99	0.99	0.99
$\hat{p}_1$	0.98983(0.003)	0.98987(0.003)	0.90095(0.003)	0.98990(0.003)	0.98993(0.003)
$\hat{p}_2$	0.99003(0.003)	0.98832(0.004)	0.98349(0.004)	0.98739(0.004)	0.98193(0.004)
$\hat{p}_2^{'}$	0.99825(0.001)	0.99757(0.002)	0.99720(0.002)	0.99815(0.001)	0.99705(0.002)
$\hat{p}_3$	0.97794(0.004)	0.97829(0.005)	0.97495(0.005)	0.97769(0.005)	0.97235(0.005)
$\hat{p}_3^{'}$	0.98803(0.003)	0.98731(0.004)	0.98744(0.004)	0.98828(0.004)	0.98709(0.003)
$\overline{MSE}$	1.27300(0.036)	1.25328(0.036)	1.31517(0.038)	1.32674(0.040)	1.34499(0.039)
SS^*_{fitted}	14.01	14.55	16.62	16.01	16.98

Table 6. Results of using $\mu = T$ and $\sigma = 1.288(\sigma^2 = 1.659)$ to generate observations.

$\mu = T$	bb,hor,h1=1m	bb,hor,h1=2m	bb,ver,h1=1m	bb,ver,h1=2m	dp,ver,h1=2.75m
p_1	0.95	0.95	0.95	0.95	0.95
$\hat{p}_1$	0.95024(0.007)	0.94967(0.006)	0.94987(0.006)	0.94967(0.007)	0.95031(0.007)
$\hat{p}_2$	0.94752(0.008)	0.94360(0.008)	0.90561(0.010)	0.92759(0.009)	0.90159(0.008)
$\hat{p}_2^{'}$	0.99795(0.001)	0.99757(0.001)	0.99634(0.002)	0.99772(0.002)	0.99637(0.002)
$\hat{p}_3$	0.90047(0.009)	0.89617(0.009)	0.86204(0.011)	0.88289(0.011)	0.85857(0.010)
$\hat{p}_3^{'}$	0.94850(0.007)	0.94770(0.007)	0.94671(0.006)	0.94829(0.008)	0.94712(0.007)
$\overline{MSE}$	1.65471(0.048)	1.63512(0.051)	1.6966(0.049)	1.71881(0.051)	1.72763(0.049)
SS^*_{fitted}	18.29	18.15	21.54	20.73	21.58

Table 7. Results of using $\mu = \hat{Y}_T$ and $\sigma = 1.123$ to generate observations.

$\mu = \hat{y}$	bb,hor,h1=1m	bb,hor,h1=2m	bb,ver,h1=1m	bb,ver,h1=2m	dp,ver,h1=2.75m
p_1	0.987153	0.988563	0.986637	0.987027	0.983998
$\hat{p}_1$	0.98725(0.004)	0.98813(0.004)	0.98639(0.004)	0.98737(0.003)	0.98401(0.004)
$\hat{p}_2$	0.98618(0.004)	0.98710(0.004)	0.96389(0.006)	0.97332(0.005)	0.94851(0.007)
$\hat{p}_2^{'}$	0.99795(0.001)	0.99757(0.001)	0.99495(0.002)	0.99591(0.002)	0.99325(0.003)
$\hat{p}_3$	0.97356(0.005)	0.97534(0.005)	0.95122(0.007)	0.96148(0.006)	0.93338(0.008)
$\hat{p}_3^{'}$	0.98458(0.004)	0.98629(0.004)	0.98160(0.005)	0.98384(0.004)	0.97802(0.005)
$\overline{MSE}$	1.25502(0.036)	1.25738(0.036)	1.22644(0.037)	1.23322(0.037)	1.22155(0.037)
SS^*_{fitted}	13.87	14.27	17.24	16.21	17.31

Table 8. Results of using $\mu = \hat{Y}_T$ and $\sigma = 1.288$ to generate observations.

$\mu = \hat{y}$	bb,hor,h1=1m	bb,hor,h1=2m	bb,ver,h1=1m	bb,ver,h1=2m	dp,ver,h1=2.75m
p_1	0.941706	0.94567	0.940543	0.941307	0.934242
$\hat{p}_1$	0.94126(0.007)	0.94517(0.006)	0.94065(0.007)	0.94087(0.007)	0.93481(0.007)
$\hat{p}_2$	0.94019(0.008)	0.94381(0.007)	0.85720(0.009)	0.88657(0.011)	0.82759(0.010)
$\hat{p}_2^{'}$	0.99769(0.001)	0.99779(0.007)	0.99516(0.002)	0.99611(0.002)	0.99401(0.003)
$\hat{p}_3$	0.88488(0.010)	0.89223(0.008)	0.80810(0.011)	0.83689(0.011)	0.77553(0.012)
$\hat{p}_3^{'}$	0.94154(0.008)	0.94396(0.008)	0.93624(0.008)	0.93701(0.008)	0.92884(0.008)
$\overline{MSE}$	1.64627(0.049)	1.64736(0.049)	1.61002(0.050)	1.61632(0.048)	1.60606(0.047)
SS^*_{fitted}	17.83	17.99	21.76	20.93	22.08

The probability p_1 in Table 5 is always fixed because we use $\sigma = 1.123$ to generate observations. Then we have the 95% confidence level that all 27 observations conform the ideal values $\pm 4dB$ and similar situation appeared in Table 6. We do not list the results of simulation in setup with Dipole antenna, horizontal, h1=2m because the ideal values are the same as that for the setup with broadband antenna, horizontal, h1=2m. From the results of simulation listed in the following four tables, we can see that the estimated probability $\hat{p}_3$ have some differences in different polarization for antenna, that is the estimated probability $\hat{p}_3$ for horizontal is always larger than that when the polarization for antenna is vertical. This phenomenon may be caused by the following two factors. That is, the scatter plot of the ideal values looks closer to be a straight line when the polarization for antenna is vertical. Or the value of the term β_2 in the estimated parameter $\hat{\beta}_T$ of the ideal values is small, especially when the polarization for the antenna is vertical. This phenomenon can be verified from the scatter plot for ideal values in Figure A.3 in the Appendix and the estimated parameter $\hat{\beta}_T$ for ideal values in Table 3.

From the four tables listed in Tables 5-8, the estimated probability $\hat{p}_3$ which express the site is qualified for measuring EMI and the estimated parameter falls into the confidence region by the conditional method. The goal in this work is using the critical value under the confidence region method to judge whether a test site is normalized or not.

H_0:27 observations conform ideal values $\pm 4dB$

H_1:some observations exceed ideal values $\pm 4dB$

Type I error represents that 27 observations come from a normalized test site, but we judge it as a non-normalized test site by the critical value of adjusted confidence region method. The estimated probability of type I error can be expressed as $\hat{p}_1 - \hat{p}_3$. Type II error represents that some observations exceed ideal values $\pm 4dB$, but we judge it as a normalized test site by the critical value of adjusted confidence region method. The estimated probability of type II error can be expressed as $\hat{p}_2 - \hat{p}_3$.

The best situation is that both two kinds of the probability of errors can be controlled. But, when we choose the critical value $F_{1-p_1,3,23}$ of the adjusted confidence region method to simulate data, the results of the two kinds of the probability of errors do not seem to be good. In order to find better results of two kinds of the probability of errors, we revise the critical value of adjusted confidence region method as 7 to do the simulation. Although, this method solved the problem of the probability of type I error, it can not reduce the probability of type II error.

The values of V_{cr} obtained from the observations for each setup is listed below. At significant level 0.01, 4.77 ($F_{0.01,3,23} = 4.765$) should be chosen as the critical value to assess whether a site is qualified for measuring EMI or not. When the polarization for antenna is vertical, we can see that for some setups with measurements exceed ideal values

$\pm 4dB$, the values of V_{cr} are smaller than 4.77. On the other hand, some setups come from a normalized test site, the values of V_{cr} are larger than 4.77. When the polarization for antenna is horizontal, we can see that only one setup with measurements do not exceed ideal values $\pm 4dB$, the value of V_{cr} is smaller than 4.77. In the remaining nine setups, the value of V_{cr} are all larger than 4.77.

Table 9. The values of V_{cr} for each setup

	OATS A	OATS B	OATS C	OATS D
broadband hor h1=1m	7.55*	10.76*	21.77*	3.11
broadband hor h1=2m	7.41*	29.13*	51.97*	7.84*
broadband ver h1=1m	4.34	2.18	2.21	0.80
broadband ver h1=1.5m	5.35*	1.85	2.59	0.18
dipole hor h1=2m	7.27*	10.26*		
dipole ver h1=2.75m	1.20	5.21*		

(_:The NSA measurements we recorded at some frequencies exceed ideal values $\pm 4dB$

*:the value of V_{cr} is larger than the critical value)

Table 10. The values of SS_{fitted} for each setup

	OATS A	OATS B	OATS C	OATS D
broadband hor h1=1m	17.14*	21.38*	53.87*	8.18
broadband hor h1=2m	11.49	17.80*	39.25*	11.19
broadband ver h1=1m	27.95*	12.78	18.92	4.38
broadband ver h1=1.5m	32.16*	9.68	12.53	0.86
dipole hor h1=2m	14.71*	24.79*		
dipole ver h1=2.75m	8.25	26.92*		

(_:The NSA measurements we recorded at some frequencies exceed ideal values $\pm 4dB$

*:the value of SS_{fitted} is larger than the critical value)

On the other hand, from the values of SS_{fitted} obtained from the observations for each setup listed in the preceding. At this place, we can use the value of SS^*_{fitted} listed in Table 5 and Table 6 as the critical value to assess the quality for the estimated parameter $\hat{\beta}_m$. Then based on the estimated MSE_m obtained from the observations, we can choose the suitable critical value to assess the quality for the estimated parameter $\hat{\beta}_m$. That is, if the MSE_m obtained from the observations is smaller, then we choose the value of SS^*_{fitted} listed in Table 5 as the critical value. Otherwise, the value of the SS^*_{fitted} listed in Table 6 should be chosen as the critical value. For using the critical value of SS^*_{fitted} listed in Table 5 and Table 6 to assess the quality of the estimated parameter $\hat{\beta}_m$, similar result will be obtained for SS_{fitted}. That is, some setups with measurements exceed ideal values $\pm 4dB$, and the value of SS_{fitted} is larger than the value of SS^*_{fitted}. On the other hand, some setups come from a normalized test site, and the value of SS_{fitted} is larger than the value of SS^*_{fitted}.

We can find that from the values of V_{cr} listed in Table 9 and the values of SS_{fitted} listed in Table 10, except the OATS A, two results show that when the polarization for antenna is horizontal, then the values of V_{cr} and SS_{fitted} are larger than that when the polarization for antenna is vertical. This is an unreasonable phenomenon because the MSE obtained from the observation is usually smaller when the polarization for antenna is horizontal, then the value of SS_{fitted} should not be too large. Since the SS_{fitted} obtained from the observations is larger (see Table 10) and MSE obtained from observations is smaller (see Table A.7) when the polarization for antenna is horizonal, so the values of V_{cr} obtained from the observations may be larger (see Table 9). These unreasonable phenomena imply that some differences exist in ideal values and the true mean of the observed values, and we denote it as bias for ideal values. Or we can say that the theoretical formula of NSA's values does not correspond to the actual situation completely, especially in low frequencies.

When the polarization for antenna is vertical, the quality of the estimated parameter influenced by the bias for ideal values do not seem to be that serious. That is because the variation for measuring is larger when the polarization for antenna is vertical, so the problem of the bias for ideal values would not be amplified. That is, once the variation for measuring is larger, then the uncertainty for EMI is more serious than the bias problem. On the other hand, the variation for measuring EMI and the estimated MSE is smaller when the polarization for antenna is horizonal. The problem of inaccuracy of the ideal values can be more easily explained since it was derived under certain conditions, then the estimated parameter influenced by the bias for ideal values will be more serious. Or we can say that the bias for ideal values does not seem to be serious when the polarization for antenna is vertical because the variation of the measurements is larger, but the bias seems to be serious when the polarization for antenna is horizontal because the variation of the measurements is smaller.

Some differences exist between results of simulation and real data. This is because the NSA measurements may be influenced by the following factors. Firstly, some differences exist in ideal values and the true mean of the observed values (ideal value is calculated under a very ideal condition, this condition does not exist in our daily life). Secondly, the measurements under low frequencies have an obvious differences than that of the high frequencies because the theoretical formula of NSA's values has neglected the effect of near field, so low frequencies are more inaccurate when measuring. Thirdly, weather factor and the quality of the test site may affect the NSA measurements. Fourthly, the differences for measuring may be caused by the accuracy level of the antenna or the measuring instrument.

4.2 Site comparison

In general, if the NSA measurements recorded at different frequencies do not exceed the ideal value $\pm 4dB$, we would regard this site as a qualified test site for measuring EMI. After using one change model fitted to the measurements and obtaining the estimation of the regression parameters, then we can calculate the value of SS_{fitted} for each setup to help to assess the quality of the estimated parameter for observations.

Table 11. The decomposition of the difference between ideal values and observations

	setup	$\sum(obs-ideal)^2$	$\sum(obs-\overline{Y})^2$	$\sum(\overline{Y}-\widehat{Y})^2$	$\sum(\widehat{Y}-ideal)^2$	others
broabband, hor,h1=1m	OATS A	109.82	20.35	31.84	56.22	1.41
	OATS B	111.77	0.77	45.62	78.75	-12.66
	OATS C	223.86	0.06	56.87	176.23	-9.29
	OATS D	76.96	0.11	60.34	29.41	-12.89
broabband, hor,h1=2m	OATS A	72.95	4.07	31.62	36.59	0.66
	OATS B	70.41	0.12	13.94	55.53	0.83
	OATS C	138.32	0.17	17.21	119.89	1.05
	OATS D	72.16	0.14	32.67	39.34	0.01
broabband, ver,h1=1m	OATS A	233.08	22.61	125.52	88.46	-3.51
	OATS B	172.59	0.31	134.40	52.92	-14.42
	OATS C	247.70	0.09	196.67	69.18	-18.24
	OATS D	132.80	0.14	125.94	19.36	-12.64
broabband, ver,h1=1.5m	OATS A	236.58	27.68	110.69	100.88	-2.68
	OATS B	140.48	0.74	119.90	33.45	-13.61
	OATS C	131.36	0.07	111.25	41.99	-21.99
	OATS D	99.30	0.09	119.54	6.97	-17.30
Dipole, hor,h1=2m	OATS A	97.67	17.69	28.84	46.26	4.88
	OATS B	157.96	1.33	54.28	90.15	12.20
Dipole, hor,h1=2.75m	OATS A	175.48	47.17	110.91	33.83	-16.43
	OATS B	192.73	3.29	115.53	88.14	-14.26

(_:The NSA measurements we recorded at some frequencies exceed ideal values $\pm 4dB$)

Table 11 shows the sum of squares difference between ideal values and observations. We decompose them into four terms as

$$\sum(obs-ideal)^2=\sum(obs-\overline{Y})^2+\sum(\overline{Y}-\widehat{Y})^2+\sum(\widehat{Y}-ideal)^2+others$$

We can find from the value of SS_{fitted} listed in Table 10 and the value of $\sum(\widehat{Y}-ideal)^2$ listed in Table 11, two results show that when the setup is with metal screen upon the ground, then the fitted values of observations are closer to the ideal values and the fitted situation for the estimated parameter $\hat{\beta}_m$ is better. Actually, when metal plane upon the ground is used to measure the EMI, then the estimation of SSE is smaller (see Table A.7). So whether the site with metal screen upon the ground is more qualified than the site with metal plane upon the ground to measure the EMI will be our future concern. For the four test sites, we regard the site OATS D as the best test site in this experiment because from many places, the model fitted or the approximated results are all quite well. On the other hand, we also regard the test site OATS C as the worst test site in this experiment because the difference between observations and ideal values in the OATS C is larger than those in the remaining three test sites. The similar results for the values of SS_{fitted} are listed in Table 10.

5 Conclusion

At present quality of OATS is determined by a comparison of measured normalized site attenuation (NSA) with the ideal values at predetermined test frequencies within the range from 30 MHz to 1000 MHz. If the deviations do not exceed $\pm 4dB$ for all the frequencies, then the OATS or alternative site is considered to be acceptable and we can use these sites to measure the EMI data. To extract more useful information about the test sites, a change point linear regression model has been developed to fit the measured data in Wang et al. (2004).

Theoretically, using the setup with metal plane to measure EMI is more suitable because the conductivity of metal plane is larger than metal screen. For our data we know that the place with metal plane which chosen to do the experiments may improve the mean square error for setups. But in some setups with metal screen we discover that the estimated parameter $\hat{\beta}_m$ for observations is closer to the estimated parameter $\tilde{\beta}_{T_m}$ for ideal values, this does not seem to be that reasonable. We are interested in knowing what causes the lower quality in the measurements with metal plane upon the ground. This will be investigated further. Although the ideal values is calculated under a very ideal condition, this condition does not exist in our daily life. The measurements of EMI are different in different environments and physical conditions. In the future, if we can collect more data and information about EMI, then we will have more knowledge about EMI measurements in different situations.

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Appendix

1. The theoretical formula of E_D^{MAX}

$$E_{DH}^{MAX} = \frac{\sqrt{49.2}(d_2^2 + d_1^2|\rho_H|^2 + 2d_1d_2|\rho_H|\cos[\Phi_H - \frac{2\pi}{\lambda}(d_2 - d_1)])^{1/2}}{d_1d_2}$$
$$E_{DV}^{MAX} = \frac{\sqrt{49.2}R^2(d_2^6 + d_1^6|\rho_V|^2 + 2d_1^3d_2^3|\rho_V|\cos[\Phi_V - \frac{2\pi}{\lambda}(d_2 - d_1)])^{1/2}}{d_1^3d_2^3}$$

where

$$\rho_H = \frac{\sin\gamma - (K - j60\lambda\sigma - \cos^2\gamma)^{1/2}}{\sin\gamma + (K - j60\lambda\sigma - \cos^2\gamma)^{1/2}} = |\rho_H|e^{i\Phi_H}$$

$$\rho_V = \frac{(K - j60\lambda\sigma)\sin\gamma - (K - j60\lambda\sigma - \cos^2\gamma)^{1/2}}{(K - j60\lambda\sigma)\sin\gamma - (K - j60\lambda\sigma - \cos^2\gamma)^{1/2}} = |\rho_V|e^{i\Phi_V}$$

$$d_1 = [R^2 + (h_2 - h_1)^2]^{1/2} \qquad d_2 = [R^2 + (h_2 + h_1)^2]^{1/2}$$

Legend :

h_1 = fixed transmit antenna height

h_2 = variable height receive antenna height

R = antenna separation relative to ground plane

K = relative dielectric constant

σ = conductivity of plane ground

ρ = reflection coefficient

φ = phase angle of reflection coefficient

λ = wavelength or frequency of interest

$\gamma = arctan(\frac{h_1+h_2}{R})$

2. The Friedman Test

data form : the data consist of b mutually independent k-variate random variables $(X_{i1}, X_{i2}, ..., X_{ik})$, called b blocks, i=1,2,...,b. The random variable X_{ij} is in block i and is associated with treatment j. Let $R(X_{ij})$ be the rank, from 1 to k, assigned to X_{ij} within block i. That is, for block i the random variables $X_{i1}, X_{i2}, ..., X_{ik}$ are compared with each other and the rank 1 is assigned to the smallest observed value, the rank 2 to the second smallest, and so on to the rank k, which is assigned to the largest observation in the block i. Ranks are assigned in all of the b blocks. Use average ranks in case of ties. Then sum the ranks for each treatment to obtain R_j where :

$$R_j = \sum_{i=1}^{b} R(X_{ij}) \qquad j = 1, 2, ...k$$

Test Statistic :

$$T = \frac{12}{bk(k+1)} \sum_{j=1}^{k} (R_j - \frac{b(k+1)}{2})^2$$

The approxiated distribution of T is the chisquared distribution with $k-1$ degrees of freedom.

Table A-1 The results of comparisons for observations in different days

antenna	polarization	h1	h2	rank		test statistics	P-value
broadband	horizontal	1m	1-4m	day1	2.78	26.419	≈ 0
				day2	1.46		
				day3	1.76		
broadband	horizontal	2m	1-4m	day1	2.22	5.143	0.076
				day2	1.67		
				day3	2.11		
broadband	vertical	1m	1-4m	day1	2.22	2.583	0.275
				day2	1.80		
				day3	1.98		
broadband	vertical	1.5m	1-4m	day1	2.22	4.667	0.097
				day2	1.67		
				day3	2.11		
dipole	horizontal	2m	1-4m	day1	2.07	0.906	0.636
				day2	1.85		
				day3	2.07		
dipole	vertical	2.75m	2.75-4m	day1	2.19	3.089	0.213
				day2	1.74		
				day3	2.07		

Table A.2 The fitted models and results for OATS A in different setups.

A.2-1 broadband hor h1=1m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 69.365 + (-28.648)t		2	3.9333	0.9770	3364.75	<0.01	196.215	112.903
1CP	y = 83.922 + (-36.44) t + 14.27 $(t-t_m)I$		4	0.6779	0.9961	6635.13	<0.01	-27.596	56.204
160	-22.169								
1JP	y = 77.789 + (-33.112) t + 5.55 I		4	1.9908	0.9887	2242.31	<0.01	59.6697	143.47
300									
2CP	y = 96.263 + (-44.196) t + 8.878 $(t-t_m)I$ + 12.92 $(t-t_n)I$		6	0.6281	0.9965	4298.32	<0.01	-31.9073	52.627
45-160	-35.291	-22.3991							

A.2-2 broadband hor h1=2m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	Y = 56.654+ (-23.848)t		2	2.4757	0.9791	3704.55	<0.01	75.403	158.715
1CP	Y = 79.128 + (-36.692) t + 15.595 $(t-t_m)I$		4	0.4634	0.9961	6710.88	<0.01	-58.389	25.411
80	-20.733								
1JP	Y = 54.873 + (-21.562) t + (-4.011) I		4	1.0814	0.9911	2861.66	<0.01	10.2352	94.0352
50									
2CP	y = 112.467 + (-58.673) t + 25.203 $(t-t_m)I$ + 12.874 $(t-t_n)I$		6	0.4154	0.9967	4494.29	<0.01	-65.384	19.1504
35-90	-33.47	-20.5961							

A.2-3 broadband ver h1=1m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	Y = 42.8961 + (-18.142)t		2	3.144	0.9553	1687.88	<0.01	94.771	178.083
1CP	Y = 37.27 + (-15.214) t + (-14.436) $(t-t_m)I$		4	1.924	0.9733	937.043	<0.01	56.891	140.691
400	-29.649								
1JP	y = 37.6414 + (-15.403) t + (-4.2783) I		4	1.8915	0.9738	953.423	<0.01	55.5247	139.325
500									
2CP	y = (-27.235) + 26.878 t + (-42.809) $(t-t_m)I$ + (-12.825) $(t-t_n)I$		6	1.708	0.9769	635.602	<0.01	49.123	133.657
35-400	-15.931	-28.755							

A.2-4 broadband ver h1=1.5m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 43.42 + (-18.259)t		2	3.144	0.9509	1530.79	<0.01	103.726	187.038
1CP	y = 34.928 + (-13.792) t + (-12.039) $(t-t_m)I$		4	1.797	0.9755	1023.02	<0.01	51.376	135.176
250	-25.831								
1JP	y = 35.985 + (-14.316) t + (-4.899) I		4	2.0103	0.9726	911.742	<0.01	60.4614	144.261
300									
2CP	y = 34.266 + (-13.423) t + (-15.78) $(t-t_m)I$ + 12.549 $(t-t_n)I$		6	1.697	0.977	651.386	<0.01	48.5941	133.128
250-600	-29.203	-16.6544							

A.2-5 dipole hor h1=2m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 58.77 + (-25.146)t		2	3.033	0.977	3361.68	<0.01	91.854	175.166
1CP	y = 83.469 + (-39.261) t + 17.538 $(t-t_m)I$		4	0.604	0.9955	5731.94	<0.01	-36.9138	46.886
80	-21.723								
1JP	y = 56.737 + (-22.534) t + (-4.5827) I		4	1.2079	0.9911	2854.46	<0.01	19.194	102.994
50									
2CP	y = 85.309 + (-40.411) t + 20.396 $(t-t_m)I$ + (-3.097) $(t-t_n)I$		6	0.566	0.996	3672.96	<0.01	-40.341	44.1932
80-250	-20.015	-23.112							

A.2-6 dipole ver h1=2.75m h2=2.75-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 51.023 + (-21.426)t		2	2.531	0.974	2925.09	<0.01	77.189	160.501
1CP	y = 37.273 + (-13.44) t + (-9.436) $(t-t_m)I$		4	2.053	0.979	1208.78	<0.01	62.192	145.962
70	-22.876								
1JP	y = 52.3704 + (-23.157) t + 3.0354 I		4	1.7612	0.98216	1413.29	<0.01	49.7447	133.545
50									
2CP	y = 56.272 + (-25.603) t + 43.811 $(t-t_m)I$ + (-41.341) $(t-t_n)I$		6	1.801	0.982	829.417	<0.01	53.411	137.946
50-60	18.208	-22.801							

Table A.3 The fitted models and results for OATS B in different setups.

A.3-1 broadband hor h1=1m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 70.279 + (-29.04)t		2	4.081	0.9768	3332.12	<0.01	115.891	199.202
1CP	y = 83.569 + (-36.078) t + 15.39 $(t-t_m)$**I**		4	0.593	0.9967	7796.03	<0.01	-38.393	45.407
200	-20.6879								
1JP	y = 76.102 + (-32.056) t + 5.647**I**		4	1.8579	0.9897	2471.99	<0.01	54.0728	137.873
600									
2CP	y = 84.213 + (-36.447) t + 11.139 $(t-t_m)$**I** + 16.325 $(t-t_n)$**I**		6	0.319	0.9982	8713.9	<0.01	-86.79	-2.256
160-600	-25.308	-8.9839							

A.3-2 broadband hor h1=2m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 58.551+ (-24.715)t		2	1.8525	0.9854	5316.79	<0.01	51.916	135.228
1CP	y = 78.994 + (-36.397) t + 14.517 $(t-t_m)$**I**		4	0.1825	0.9985	18228.3	<0.01	-133.868	-50.068
80	-21.8807								
1JP	y = 57.7895 + (-22.886) t + (-3.847)**I**		4	0.6364	0.9951	5209.97	<0.01	-32.7081	51.0919
45									
2CP	y = 78.328 + (-35.981) t + 13.612 $(t-t_m)$**I** + 14.583 $(t-t_n)$**I**		6	0.12	0.9991	16655.1	<0.01	-166.025	-81.491
80-800	-22.369	-7.7866							

A.3-3 broadband ver h1=1m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 45.094 + (-19.118)t		2	2.105	0.9726	2800.34	<0.01	62.253	145.565
1CP	y = 33.154 + (-12.183) t + (-8.194) $(t-t_m)$**I**		4	1.749	0.9778	1128.99	<0.01	49.203	133.003
70	-20.377								
1JP	y = 46.3419 + (-20.721) t + 2.81187**I**		4	1.4425	0.9817	1374.74	<0.01	33.5734	117.373
50									
2CP	y = 96.9979 + (-53.462) t + (52.311) $(t-t_m)$**I** + (-19.735) $(t-t_n)$**I**		6	1.0331	0.9872	1158.25	<0.01	8.400	92.934
40-70	-1.151	-20.886							

A.3-4 broadband ver h1=1.5m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 46.784 + (-19.693)t		2	2.1907	0.9731	2854.47	<0.01	65.498	148.809
1CP	y = 41.571 + (-16.95) t + (-7.3912) $(t-t_m)$**I**		4	1.5668	0.9812	1341.55	<0.01	40.2694	124.069
250	-24.3412								
1JP	y = 41.9076 + (-17.107) t + 5.647 I		4	1.5624	0.9813	1345.39	<0.01	40.0422	123.842
300									
2CP	y = 113.682 + (-64.122) t + 48.618 $(t-t_m)$**I** + (-8.192) $(t-t_n)$**I**		6	1.2974	0.9849	975.674	<0.01	26.855	111.389
35-200	-15.504	-23.6952							

A.3-5 dipole hor h1=2m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 55.102 + (-23.847)t		2	1.7914	0.9848	5119.33	<0.01	49.1957	132.507
1CP	y = 80.239 + (-38.749) t + 16.745 $(t-t_m)$**I**		4	0.7221	0.994	4272.67	<0.01	-22.4701	61.33
60	-22.0041								
1JP	y = 53.751 + (-22.011) t + (-3.305)**I**		4	0.9977	0.9917	3085.43	<0.01	3.71339	87.5134
50									
2CP	y = 85.508 + (-40.843) t + 20.476 $(t-t_m)$**I** + (-3.305) $(t-t_n)$**I**		6	0.659	0.995	2813.18	<0.01	-28.0725	56.4617
60-250	-20.367	-23.672							

A.3-6 dipole ver h1=2.75m h2=2.75-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y = 52.516 + (-22.421)t		2	1.821	0.983	4452.01	<0.01	50.514	133.826
1CP	y = 46.981 + (-19.4) t + (-4.692) $(t-t_m)$**I**		4	1.543	0.986	1756.36	<0.01	39.039	122.839
125	-24.0916								
1JP	y = 55.247 + (-24.744) t + 3.23768**I**		4	0.8806	0.99178	3096.99	<0.01	-6.3971	77.4029
70									
2CP	y = 77.251 + (-38.35) t + 56.008 $(t-t_m)$**I** + (-42.14) $(t-t_n)$**I**		6	0.4351	0.996	3777.48	<0.01	-61.647	22.8872
50-60	17.658	-22.801							

Table A.4 The fitted models and results for OATS C in different setups.

A.4-1 broadband hor h1=1m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y =71.398+(-29.304)t		2	4.8565	0.9730	2851.24	<0.01	129.98	213.292
1CP	y =85.839+(-36.952)t + (16.723) $(t-t_m)$**I**		4	0.7394	0.9959	6390.03	<0.01	-20.5613	63.2387
200	-20.228								
1JP	y =79.237+(-33.389)t + (6.3829)**I**		4	2.0120	0.9891	2331.93	<0.01	60.5281	144.328
500									
2CP	y =86.608+(-37.392) t+ (11.933) $(t-t_m)$**I**+ (11.925) $(t-t_n)$**I**		6	0.5345	0.9972	5310.01	<0.01	-44.9769	39.5573
160-500	-24.459	-13.534							

A.4-2 broadband hor h1=2m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y =58.343+(-24.386)t		2	2.494	0.9799	3845.63	<0.01	75.9845	159.296
1CP	y =82.163+(-37.999)t + (16.915) $(t-t_m)$**I**		4	0.2256	0.9982	14432.6	<0.01	-116.703	-32.9033
80	-21.084								
1JP	y =56.310+(-21.775)t + (-4.579)**I**		4	0.6574	0.9948	4936.31	<0.01	-30.077	53.723
50									
2CP	y =80.219+(-36.786)t + (29.249) $(t-t_m)$**I** + (-13.795) $(t-t_n)$**I**		6	0.1637	0.9988	11939.2	<0.01	-140.807	-56.2732
100-125	-7.537	-21.332							

A.4-3 broadband ver h1=1m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y =45.841+(-19.255)t		2	2.6323	0.9664	2271.26	<0.01	80.37	163.682
1CP	y =45.236+(-18.946)t + (-45.886) $(t-t_m)\mathbf{I}$		4	2.5553	0.9682	781.353	<0.01	79.8888	163.689
900	-64.832								
1JP	y =46.781+(-20.461)t + (2.116)		4	2.2946	0.9714	873.029	<0.01	71.1735	154.973
400									
2CP	y =74.987+(-38.144)t + (66.323) $(t-t_m)\mathbf{I}$ + (48.461) $(t-t_n)\mathbf{I}$		6	1.9675	0.9761	631.88	<0.01	60.5822	145.116
50-60	28.178	-20.282							

A.4-4 broadband ver h1=1.5m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y =46.373+(-19.442)t		2	1.7114	0.9783	3561.48	<0.01	45.498	128.81
1CP	y =42.854+(-17.591)t + (-4.988) $(t-t_m)\mathbf{I}$		4	1.4458	0.9821	1410.81	<0.01	33.7569	117.557
250	-22.579								
1JP	y =49.766+(-21.649)t + 2.496$\mathbf{I}$		4	1.1934	0.9853	1714.51	<0.01	18.2217	102.022
120									
2CP	y =67.145+(-32.655) t + (18.218) $(t-t_m)\mathbf{I}$ + (-8.357) $(t-t_n)\mathbf{I}$		6	1.0434	0.9874	1179.27	<0.01	9.2057	93.74
50-200	-14.443	-22.799							

Table A.5 The fitted models and results for OATS D in different setups.

A.5-1 broadband hor h1=1m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y =68.998+ (-28.585)t		2	4.5228	0.9736	2913.27	<0.01	124.214	207.525
1CP	y =86.288+ (-37.93) t + (15.594) $(t-t_m)$**I**		4	0.7850	.9955	5720.69	<0.01	-15.7061	68.0939
140	-22.336								
1JP	y = 67.91 + (-25.97) t + (-5.504)**I**		4	2.0522	0.98832	2172.56	<0.01	62.128	145.928
45									
2CP	y = 85.53 + (-37.48) t + (13.616) $(t-t_m)$**I** + (34.323) $(t-t_n)$**I**		6	0.4579	0.9975	5896.25	<0.01	-57.5062	27.0281
140-800	-23.863	10.460							

A.5-2 broadband hor h1=2m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y =58.612+(-24.939)t		2	2.3658	0.9817	4329.21	<0.01	71.7242	155.036
1CP	y=84.99+(-40.263)t +(18.105)$(t-t_m)$**I**		4	0.4261	0.9968	7966.45	<0.01	-65.2052	18.5948
70	-22.156								
1JP	y = 57.76 + (-22.88) t + (-4.3308)**I**		4	0.8249	0.9937	4101.98	<0.01	-11.6847	72.1153
45									
2CP	y = 83.90 + (-39.57) t + (16.788) $(t-t_m)$**I** + (19.784) $(t-t_n)$**I**		6	0.3115	0.9977	6544.22	<0.01	-88.7095	-4.17522
70-800	-22.783	-2.999							

A.5-3 broadband ver h1=1m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y =46.384+(-19.687)t		2	1.7047	0.9789	3666.27	<0.01	45.1814	128.493
1CP	y =44.453+(-18.676)t +(-3.332) $(t-t_m)$**I**		4	1.6375	0.9803	1274.06	<0.01	43.8422	127.642
300	-22.009								
1JP	y = 43.103+(-17.964) t +(-2.356)**I**		4	1.3619	0.9836	1536.99	<0.01	28.9191	112.719
400									
2CP	y = 43.370+(-18.089)t + (-24.474) $(t-t_m)$**I** + (41.428) $(t-t_n)$**I**		6	0.9866	0.9884	1279.32	<0.01	4.6713	89.2056
400-600	-42.563	-1.135							

A.5-4 broadband ver h1=1.5m h2=1-4m

Model			m	MSE	R^2	F	p-value	AIC	AICc
SL	y =47.148+(-20.035)t		2	1.6770	0.9799	3859.48	<0.01	43.8548	127.166
1CP	y =43.706+(-18.224) t + (-4.881) $(t-t_m)$**I**		4	1.4237	0.9834	1520.73	<0.01	32.514	116.314
250	-23.105								
1JP	y =50.629+(-22.155) t + 2.314		4	1.2558	0.9854	1727.55	<0.01	22.3463	106.146
140									
2CP	y = 43.702+ (-18.219) t + (-20.796) $(t-t_m)$**I** + (29.578) $(t-t_n)$**I**		6	1.1781	0.9866	1106.32	<0.01	19.0402	103.574
400-600	-39.051	-9.437							

Table A.6 Results of SSE for using one change point model fitted to measurements each day respectively.

	OATS A	OATS B	OATS C	OATS D
Bb,hor,h1=1m	52.1955	45.6818	56.931	60.4479
	13.8239	15.5492	19.1048	20.4477
	10.518	14.9558	19.0648	19.8467
	13.4067	15.1705	18.7594	20.148
Bb,hor,h1=2m	35.6885	14.0551	17.3727	32.8083
	10.6847	4.94227	5.24081	10.4122
	11.9561	4.43016	5.93691	11.1528
	11.4482	4.6627	6.16161	11.2191
Bb,ver,h1=1m	148.123	134.71	196.756	126.084
	61.9148	45.1267	66.191	42.1361
	41.7931	44.4516	65.8152	41.4194
	39.8525	45.0573	64.7469	42.4991
Bb,ver,h1=1.5m	138.373	120.643	111.323	109.628
	55.1821	40.8825	36.6887	36.523
	42.2807	39.0119	37.148	36.6253
	37.7917	40.5706	37.4731	36.4738
Dp,hor,h1=2m	46.5235	55.6051		
	11.5588	16.8833		
	15.163	19.6996		
	17.7443	18.957		
Dp,ver,h1=2.75m	158.082	118.824		
	44.078	35.5563		
	58.7295	41.2762		
	43.6523	41.5665		

SSE_{Tot}
SSE_{1st}
SSE_{2nd}
SSE_{3rd}

Table A.7 The summary of using one change point model fitted to the measurements for each setups.

Setup \ Site	OATS A				OATS B			
Bb hor h1=1m	83.9	-36.4	14.27		83.6	-36	15.4	
	160	0.68	52.4	-22.1	200	0.59	48.1	-20.6
Bb hor h1=2m	79.1	-36.7	15.6		78.9	-36.4	14.5	
	80	0.46	49.4	-21.1	80	0.18	51.3	-21.9
Bb ver h1=1m	* 37.3	-15.2	-14.4		* 33.2	-12.2	-8.2	
	400	1.92	74.8	-29.6	70	1.79	48.3	-20.4
Bb ver h1=1.5m	* 34.9	-13.8	-12		41.6	-16.9	-7.4	
	250	1.80	63.7	-25.8	250	1.57	59.3	-24.3
Db hor h1=2m	83.5	-39.3	17.5		80.2	-38.7	16.7	
	80	0.60	50.2	-21.8	60	0.72	50.5	-22
Db ver h1=2.75m	37.4	-13.4	-9.4		46.9	-19.4	-4.6	
	70	2.05	54.7	22.8	125	1.54	56.7	-24.1

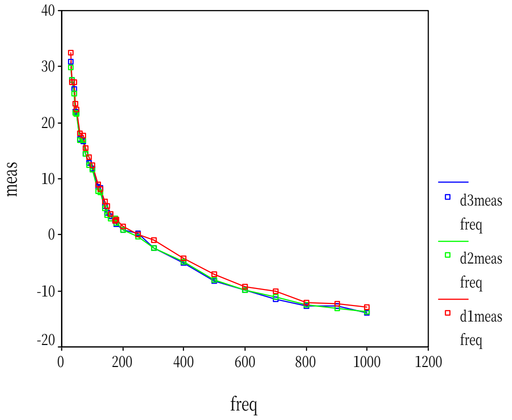
Setup \ Site	OATS C				OATS D			
Bb hor h1=1m	* 85.8	-36.9	16.7		86.3	-37.9	15.6	
	200	0.74	47.3	-20.2	140	0.79	52.8	-22.3
Bb hor h1=2m	82.2	-37.9	16.9		84.9	-40.3	18.1	
	80	0.23	50.0	-21.0	70	0.43	50.5	-22.2
Bb ver h1=1m	* 45.2	-18.9	-45.9		44.5	-18.7	-3.3	
	900	2.56	134.9	-64.8	300	1.64	52.7	-22
Bb ver h1=1.5m	42.9	-17.6	-4.9		43.7	-18.2	-4.9	
	250	1.45	54.6	-22.5	250	1.43	55.4	23.1

(***: The NSA measurements we recorded at some frequencies exceed ideal values** $\pm 4dB$)

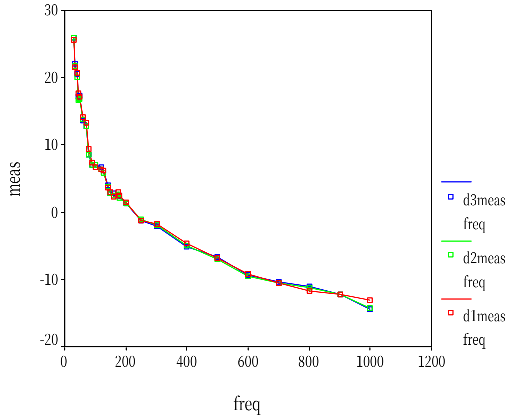
$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	
Cp	MSE	$\hat{\beta}_0 - \hat{\beta}_2 t_m$	$\hat{\beta}_1 + \hat{\beta}_2$

A.1-1 The scatter plots of measurements versus frequency for OATS A

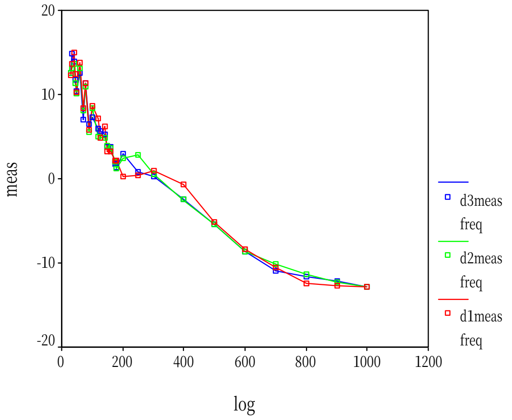
Broadband,hor,h1=1M,h2=1-4M



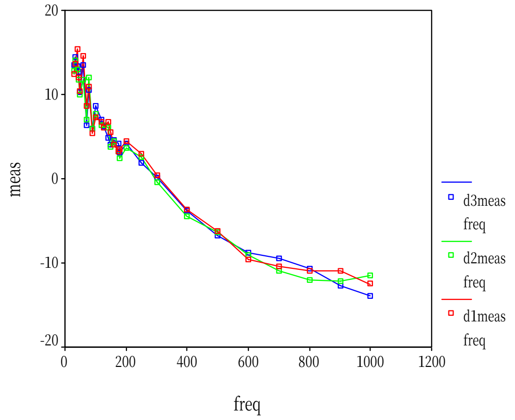
Broadband,hor,h1=1M,h2=1-4M



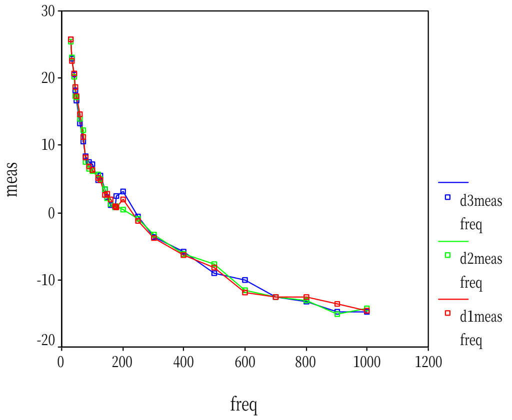
Broadband,ver,h1=1M,h2=1-4M



Broadband,ver,h1=1.5M,h2=1-4M



Diploe,hor,h1=2M,h2=1-4M



Dipole,hor,h1=2.75M,h2=2.75-4M

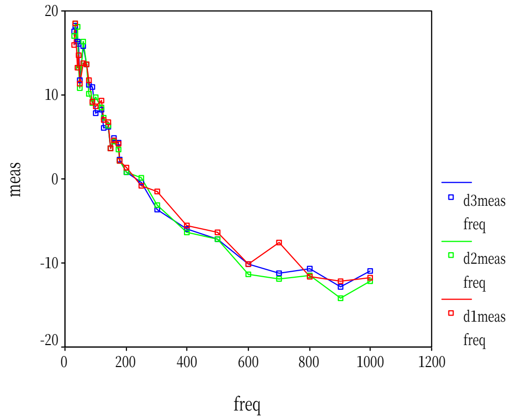
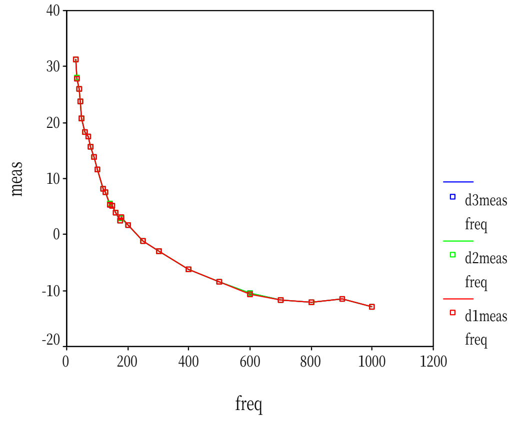


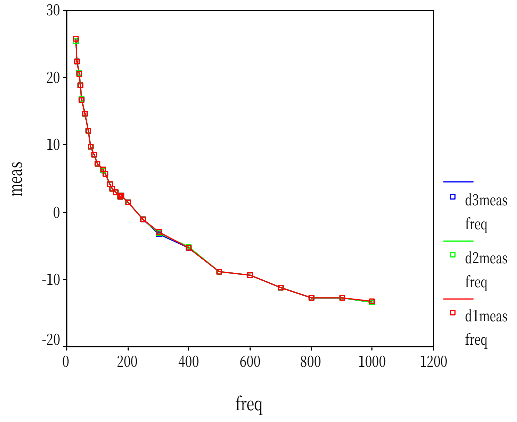
Figure A-1 The scatter plots of measurements versus frequency

A.1-2 The scatter plots of measurements versus frequency for OATS B

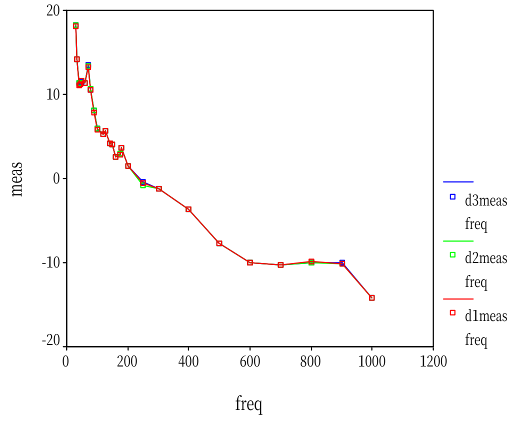
Broadband,hor,h1=1M,h2=1-4M



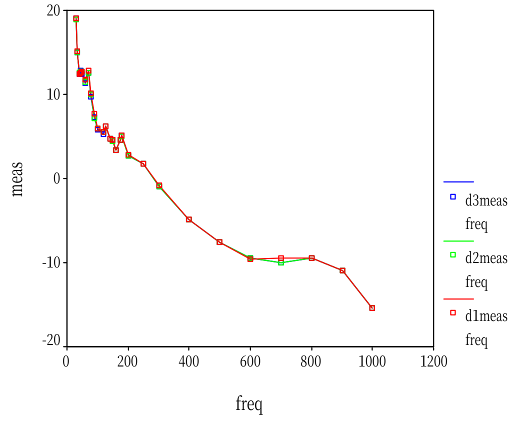
Broadband,hor,h1=1M,h2=1-4M



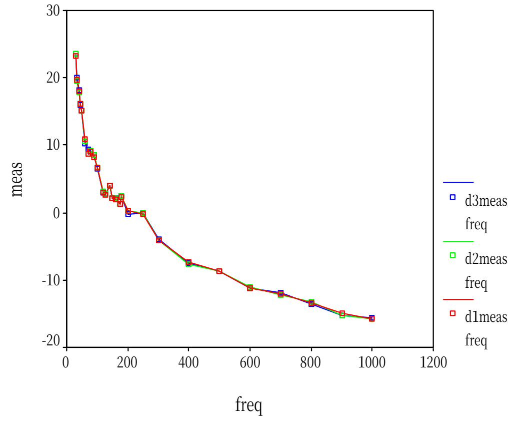
Broadband,ver,h1=1M,h2=1-4M



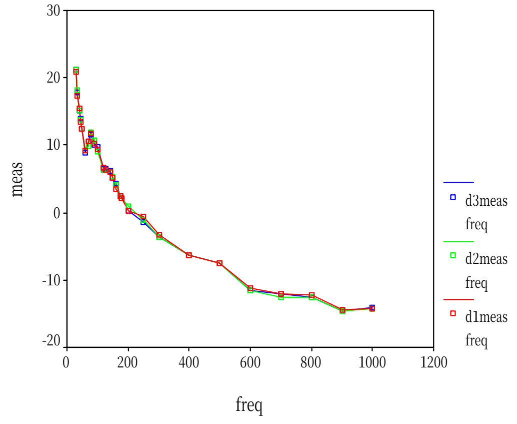
Broadband,ver,h1=1.5M,h2=1-4M



Diploe,hor,h1=2M,h2=1-4M

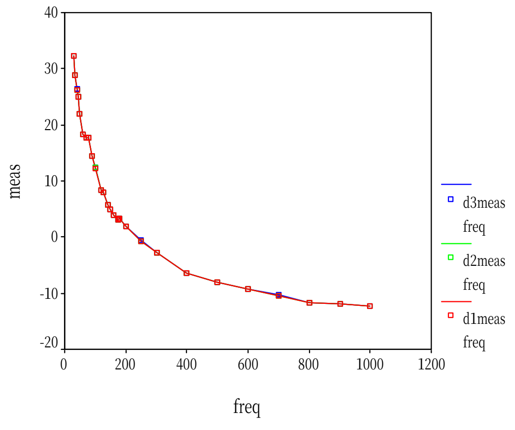


Dipole,hor,h1=2.75M,h2=2.75-4M

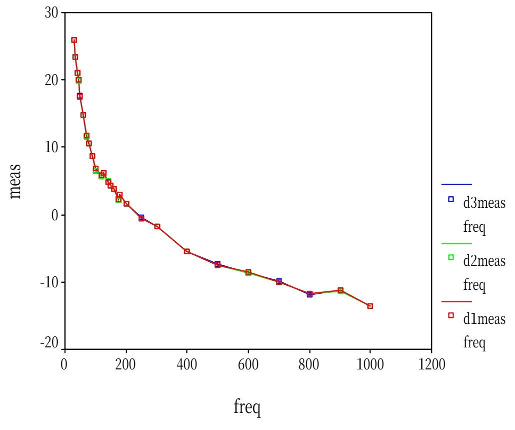


A.1-3 The scatter plots of measurements versus frequency for OATS C

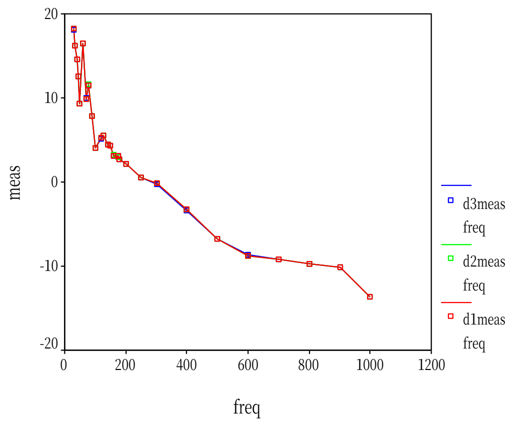
Broadband,hor,h1=1M,h2=1-4M



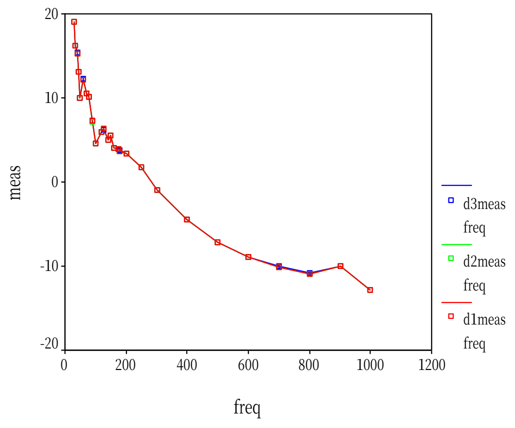
Broadband,hor,h1=1M,h2=1-4M



Broadband,ver,h1=1M,h2=1-4M

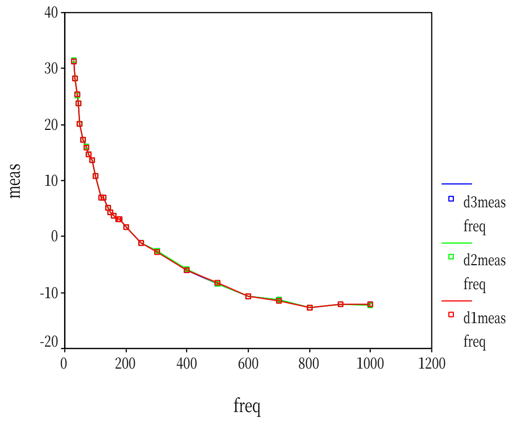


Broadband,ver,h1=1.5M,h2=1-4M

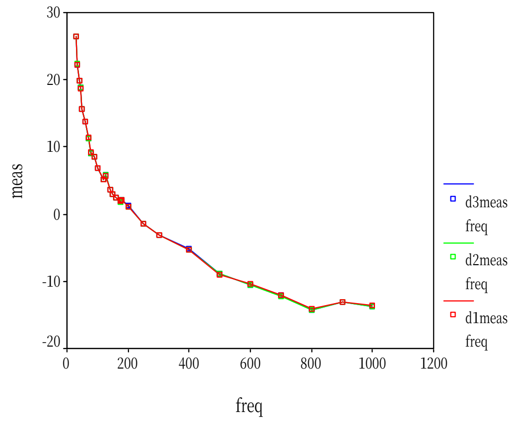


A.1-4 The scatter plots of measurements versus frequency for OATS D

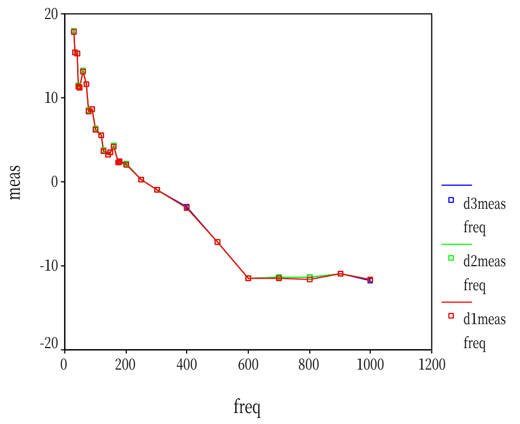
Broadband,hor,h1=1M,h2=1-4M



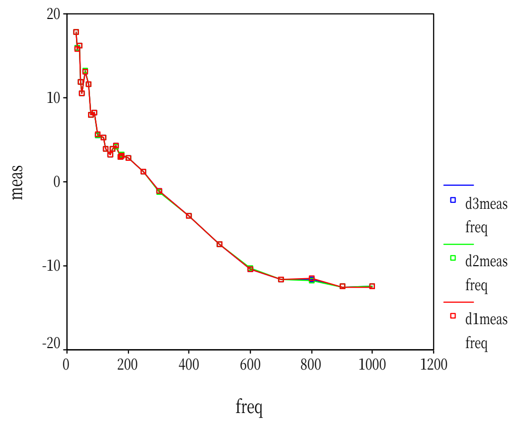
Broadband,hor,h1=1M,h2=1-4M



Broadband,ver,h1=1M,h2=1-4M

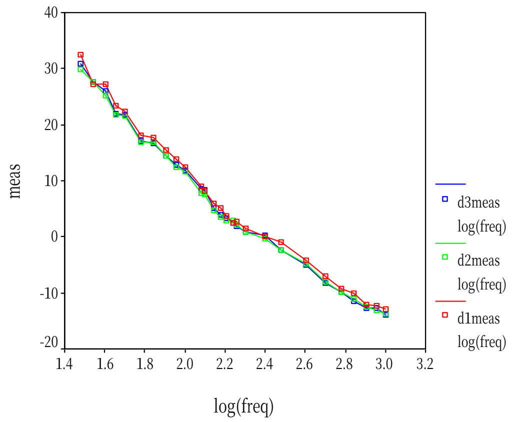


Broadband,ver,h1=1.5M,h2=1-4M

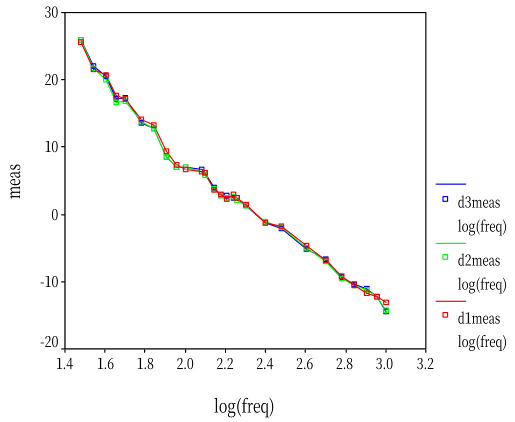


A.2-1 The scatter plots of measurements versus log(frequency) for OATS A

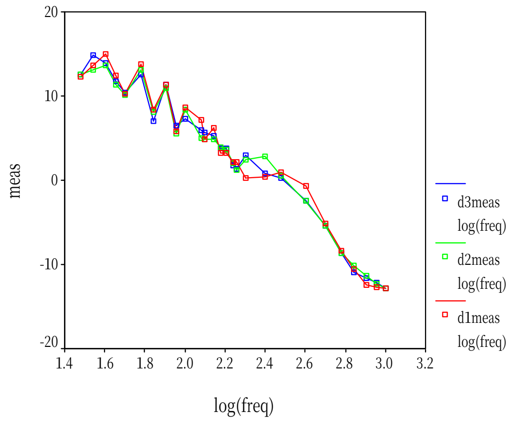
Broadband,hor,h1=1M,h2=1-4M



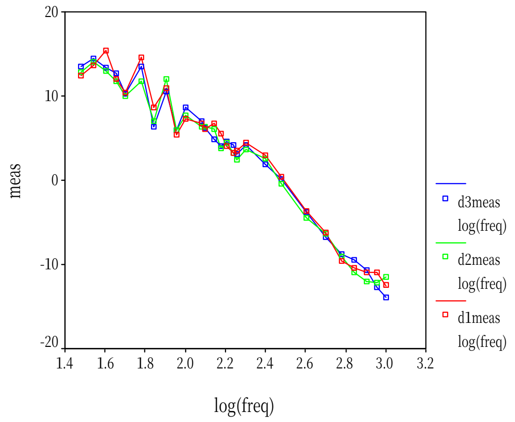
Broadband,hor,h1=1M,h2=1-4M



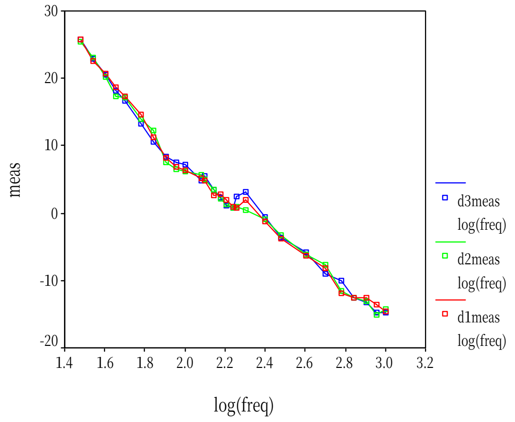
Broadband,ver,h1=1M,h2=1-4M



Broadband,ver,h1=1.5M,h2=1-4M



Diploe,hor,h1=2M,h2=1-4M



Dipole,hor,h1=2.75M,h2=2.75-4M

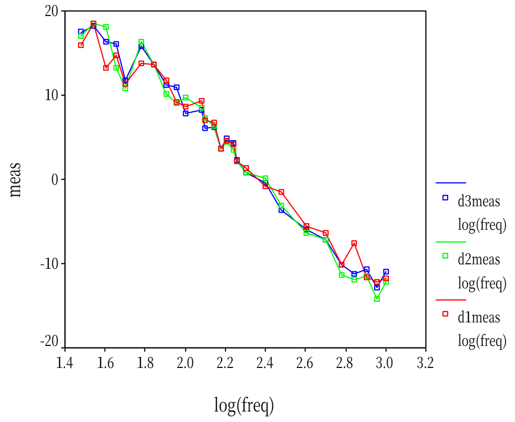
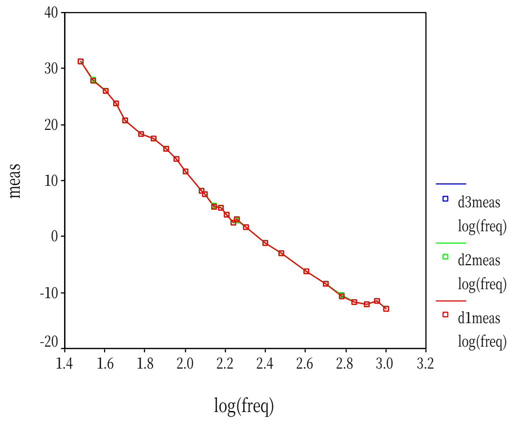


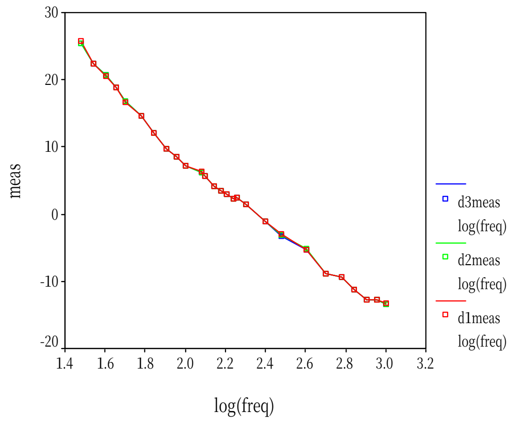
Figure A.2 The scatter plots of measurements versus log(frequency)

A.2-2 The scatter plots of measurements versus log(frequency) for OATS B

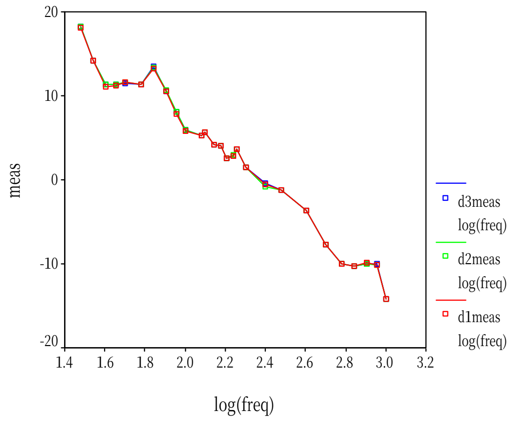
Broadband,hor,h1=1M,h2=1-4M



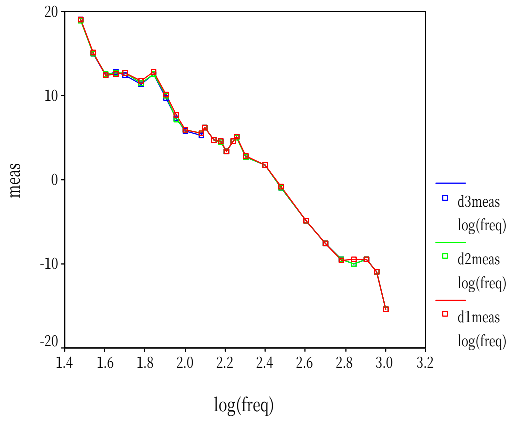
Broadband,hor,h1=1M,h2=1-4M



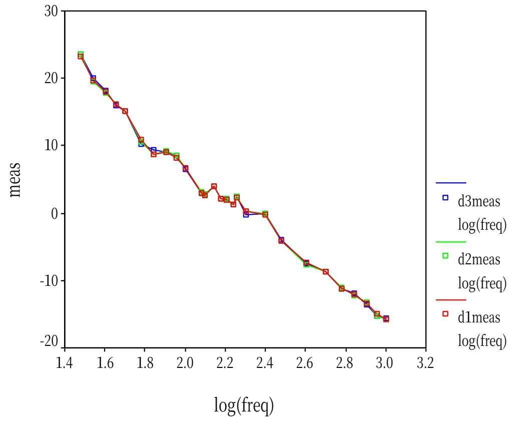
Broadband,ver,h1=1M,h2=1-4M



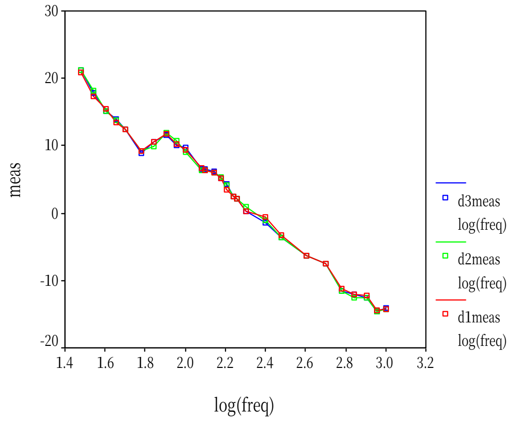
Broadband,ver,h1=1.5M,h2=1-4M



Diploe,hor,h1=2M,h2=1-4M

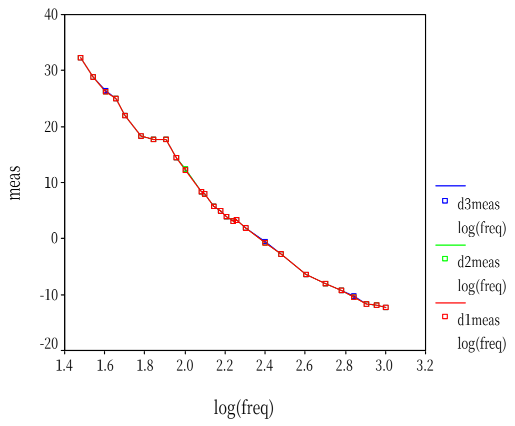


Dipole,hor,h1=2.75M,h2=2.75-4M

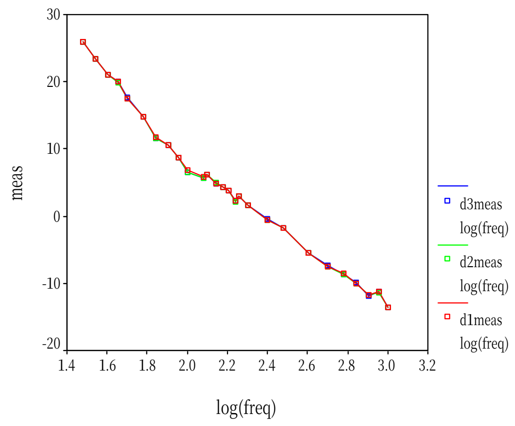


A.2-3 The scatter plots of measurements versus log(frequency) for OATS C

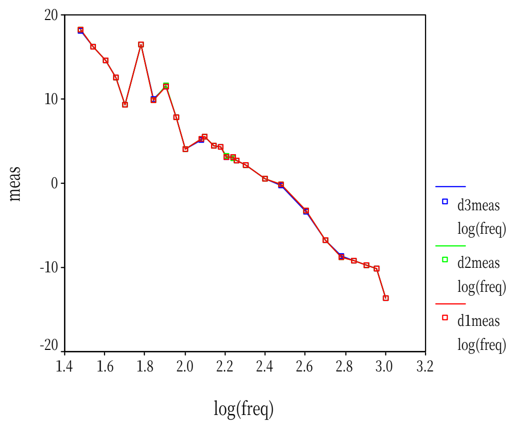
Broadband,hor,h1=1M,h2=1-4M



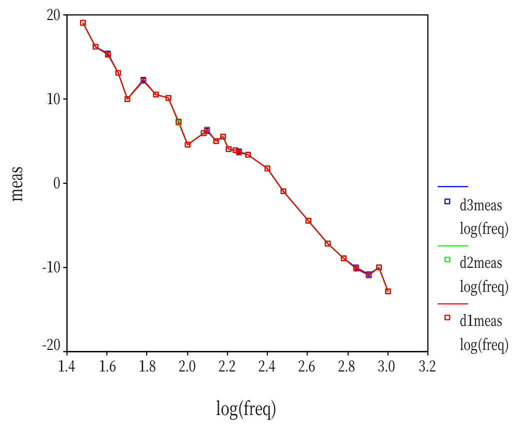
Broadband,hor,h1=1M,h2=1-4M



Broadband,ver,h1=1M,h2=1-4M

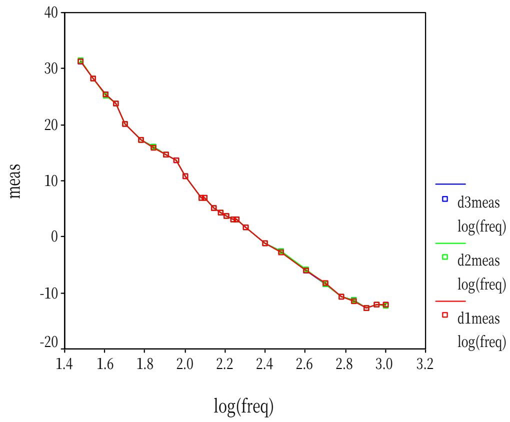


Broadband,ver,h1=1.5M,h2=1-4M

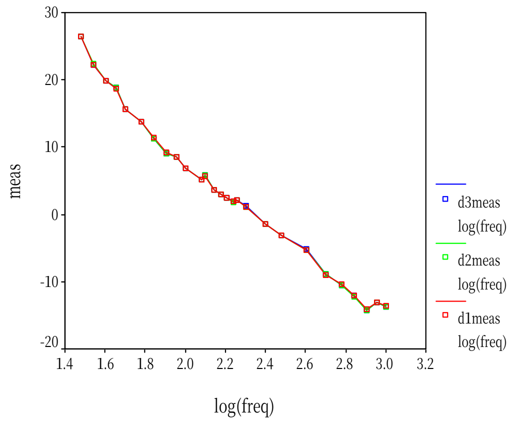


A.2-4 The scatter plots of measurements versus log(frequency) for OATS D

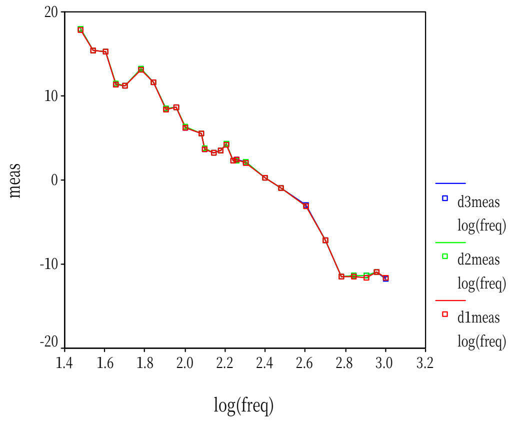
Broadband,hor,h1=1M,h2=1-4M



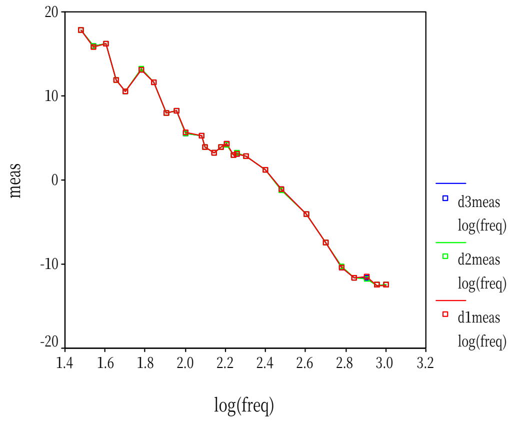
Broadband,hor,h1=1M,h2=1-4M



Broadband,ver,h1=1M,h2=1-4M



Broadband,ver,h1=1M,h2=1-4M



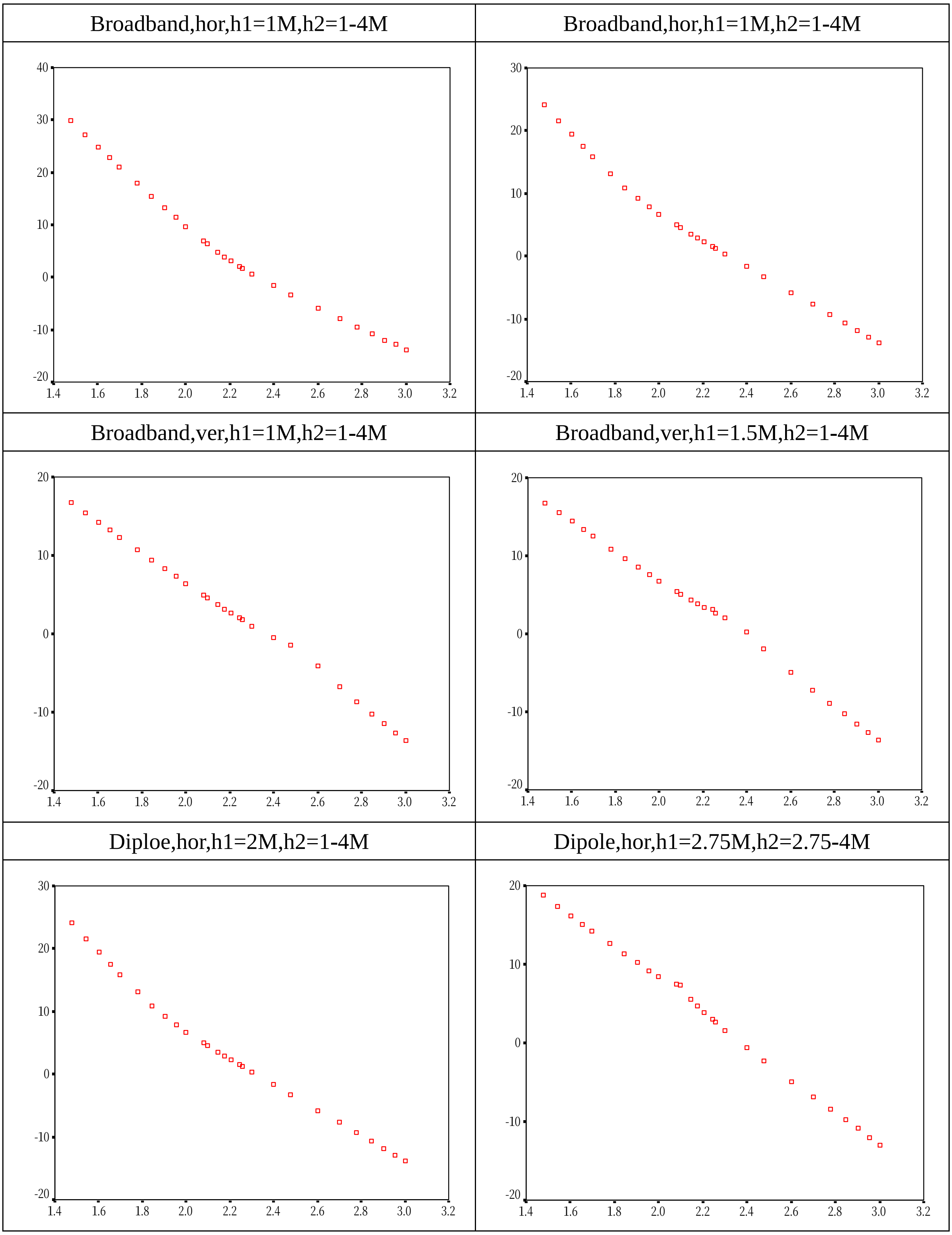


Figure A.3 The scatter plots of theoretically value versus Log(frequency)

A.4-1 For using $\mu = T$ and $\sigma = 1.123$ to generate data

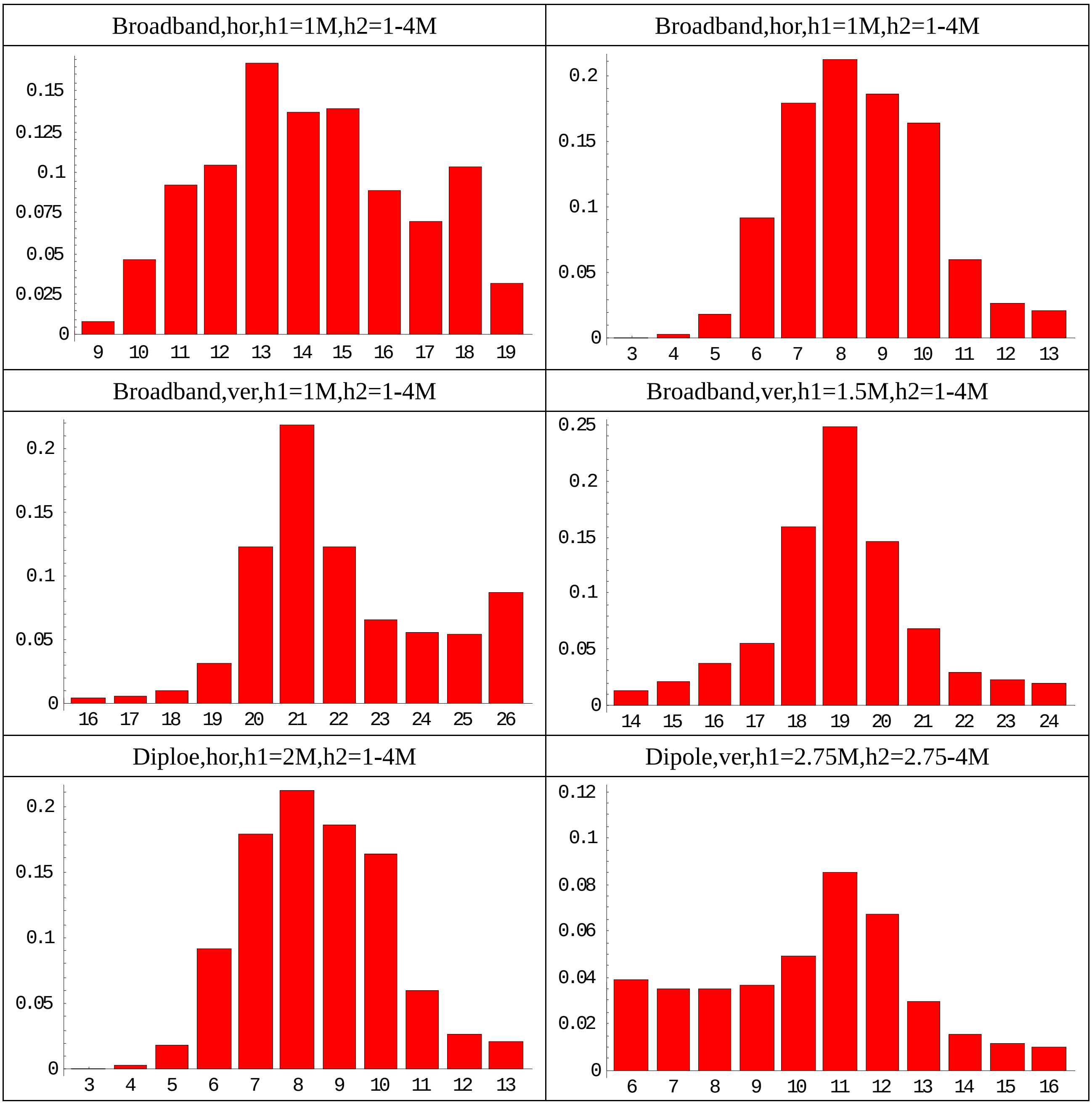
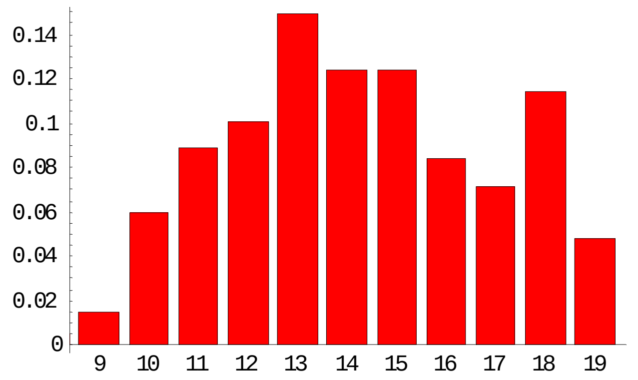
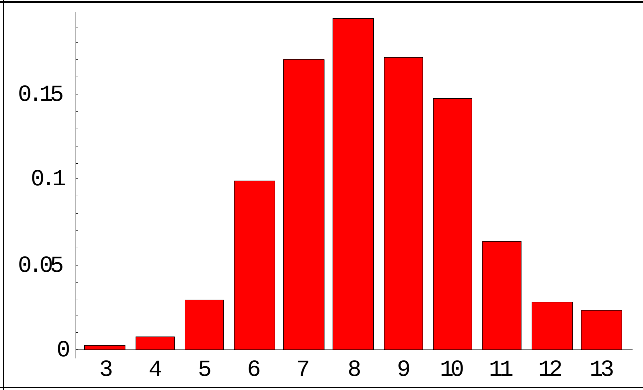
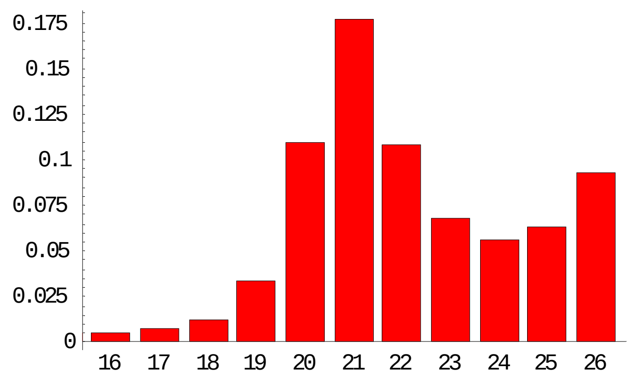
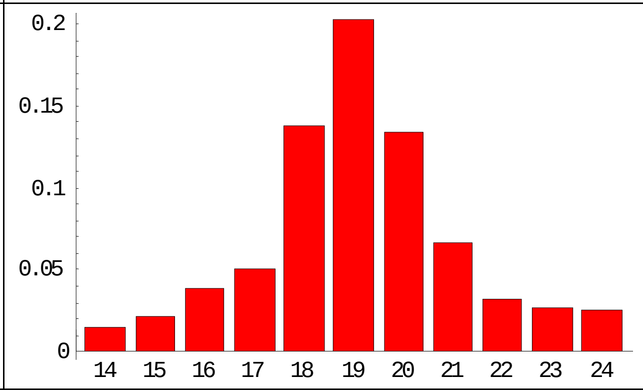
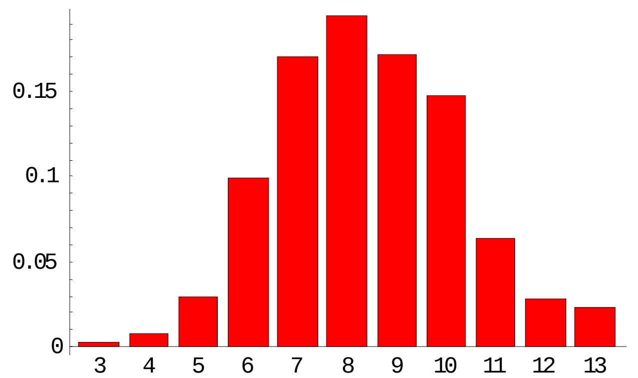
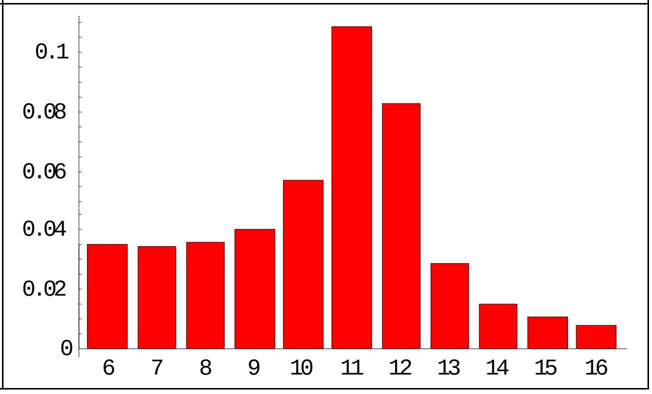


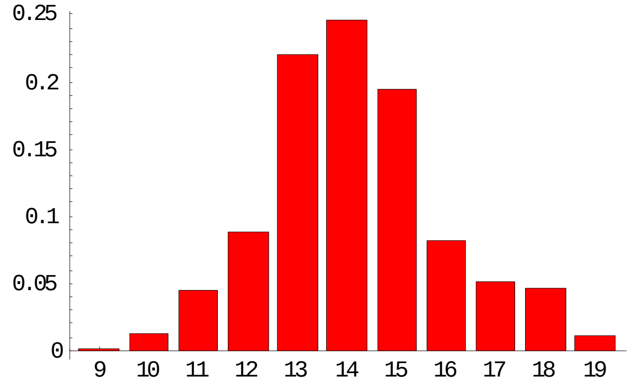
Figure A.4 The histogram plots of the probability of change point location versus frequency

A.4-2 For using $\mu = T$ and $\sigma = 1.288$ to generate data

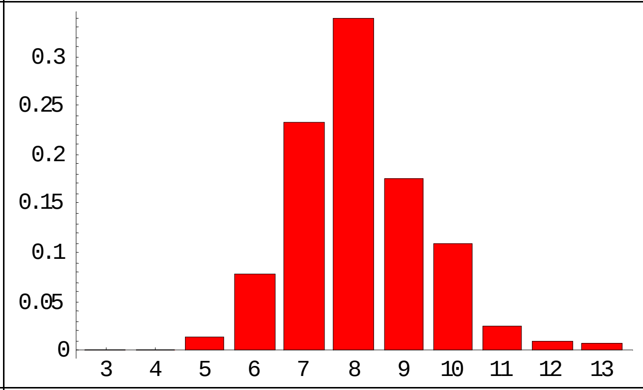
Broadband,hor,h1=1M,h2=1-4M	Broadband,hor,h1=1M,h2=1-4M
	
Broadband,ver,h1=1M,h2=1-4M	Broadband,ver,h1=1.5M,h2=1-4M
	
Diploe,hor,h1=2M,h2=1-4M	Dipole,ver,h1=2.75M,h2=2,75-4M
	

A.4-3 For using $\mu = \hat{y}_T$ and $\sigma = 1.123$ to generate data

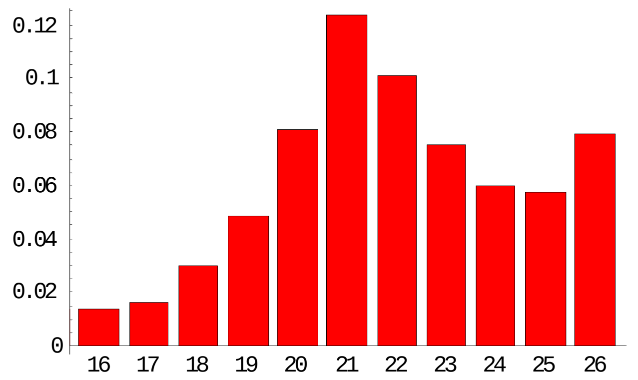
Broadband,hor,h1=1M,h2=1-4M



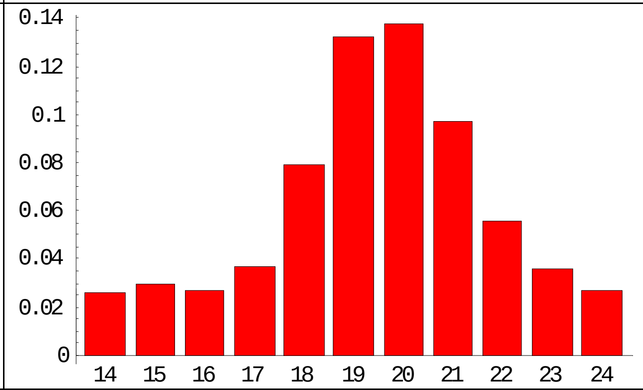
Broadband,hor,h1=2M,h2=1-4M



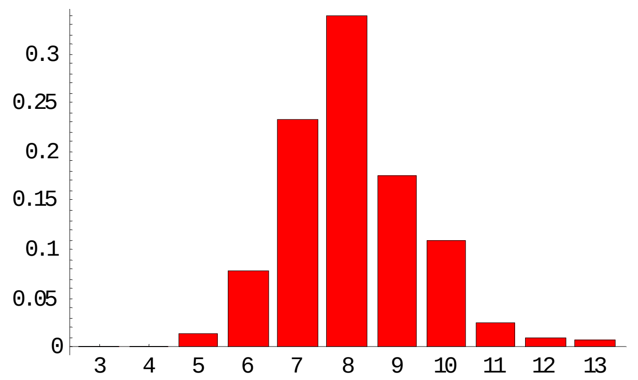
Broadband,ver,h1=1M,h2=1-4M



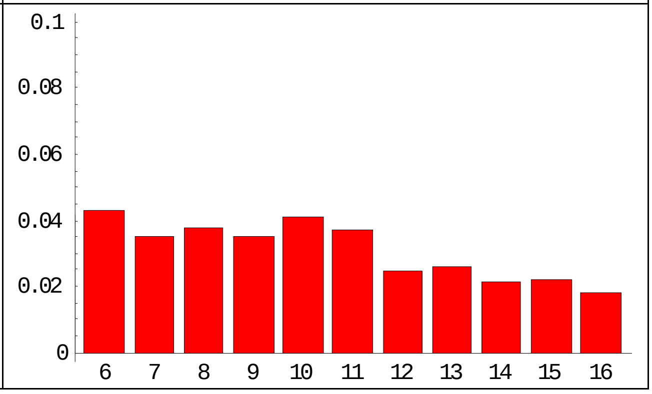
Broadband,ver,h1=1.5M,h2=1-4M



Diploe,hor,h1=2M,h2=1-4M

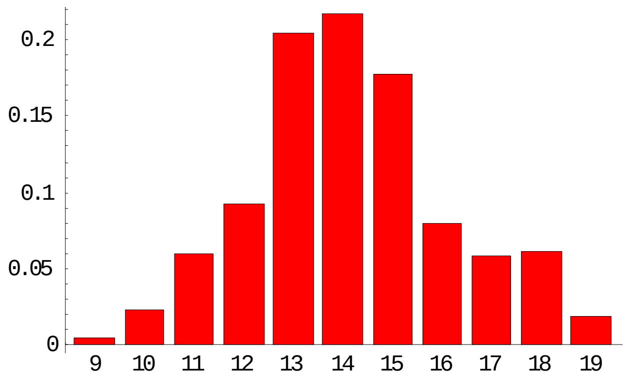


Diploe,ver,h1=2.75M,h2=2.75-4M

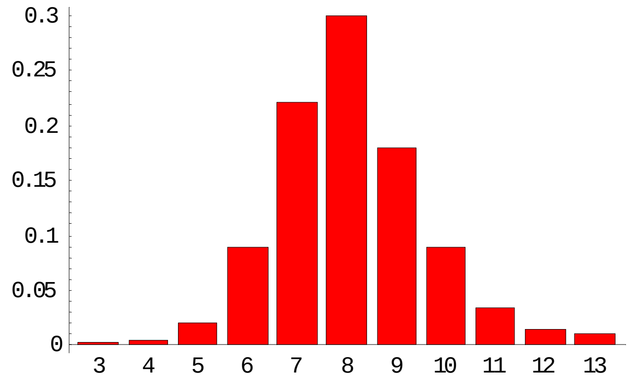


A.4-4 For using $\mu = \hat{y}_T$ and $\sigma = 1.288$ to generate data

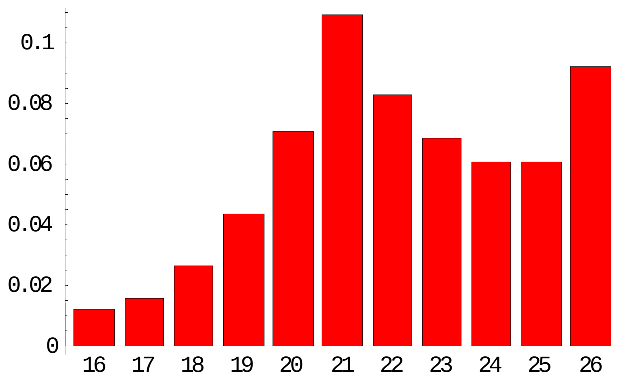
Broadband,hor,h1=1M,h2=1-4M



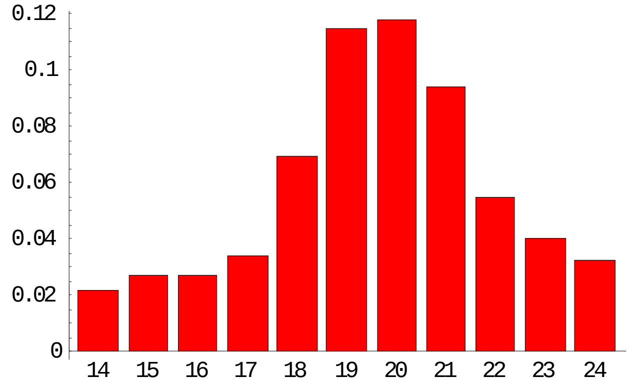
Broadband,hor,h1=2M,h2=1-4M



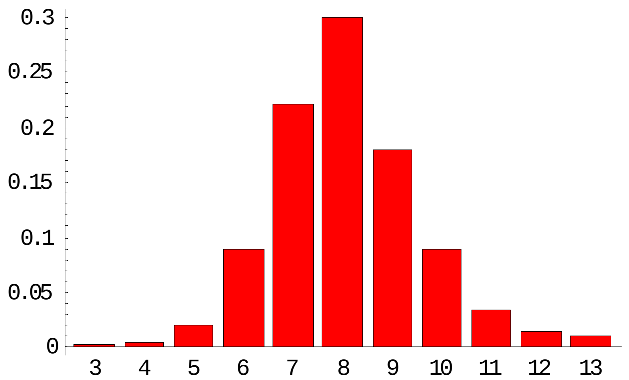
Broadband,ver,h1=1M,h2=1-4M



Broadband,ver,h1=1.5M,h2=1-4M



Diploe,ver,h1=2M,h2=1-4M



Diploe,ver,h1=2.75M,h2=2.75-4M

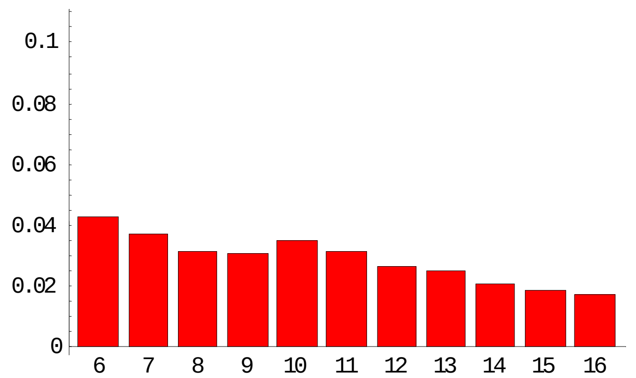


Table A.8-1 Results of using the ideal values to fit one change point model for all frequencies

Setup	Broadband,hor,h1=1M,h2=1-4M				Broadband,hor,h1=2M,h2=1-4M			
t_m	β_0	β_1	β_2	MSE	β_0	β_1	β_2	MSE
35	169.509	−94.5821	67.1043	4.11965	148.045	−83.9098	60.902	1.58316
40	137.353	−72.3523	45.3591	3.57153	117.765	−63.0415	40.4565	1.16847
45	123.881	−63.0515	36.541	3.05915	104.424	−53.9252	31.7337	0.836011
50	116.541	−57.9906	31.9787	2.56379	96.8256	−48.7851	26.9748	0.561115
60	106.725	−51.3946	26.1888	1.83175	87.0732	−42.3482	21.11	0.228422
70	100.566	−47.3469	22.7531	1.35043	81.1095	−38.5053	17.655	0.0838002
80	96.5615	−44.7476	20.6999	0.97891	77.1644	−36.0096	15.4668	0.0307903
90	93.7243	−42.9284	19.3938	0.683117	74.3356	−34.2506	13.9685	0.0314505
100	91.5834	−41.573	18.5328	0.447454	72.1875	−32.9362	12.8837	0.0664048
120	88.1074	−39.4271	17.1928	0.18126	68.9316	−30.9845	11.2548	0.194883
125	87.4094	−39.0028	16.9524	0.143706	68.3149	−30.6196	10.962	0.228002
140	85.6859	−37.9667	16.4831	0.070573	66.8194	−29.7436	10.3149	0.324942
150	84.7121	−37.3901	16.2662	0.0605294	66.0137	−29.2773	9.9946	0.388787
160	83.9	−36.9144	16.1649	0.0694088	65.3605	−28.9024	9.78118	0.446976
175	82.8726	−36.3204	16.1388	0.113453	64.5643	−28.4501	9.58314	0.52759
180	82.5978	−36.163	16.1859	0.131689	64.3573	−28.3334	9.56451	0.550217
200	81.7454	−35.6802	16.5998	0.211713	63.7272	−27.9811	9.66266	0.62644
250	79.8973	−34.6571	17.7024	0.519106	62.4595	−27.2846	10.0323	0.807569
300	78.3667	−33.8253	18.9103	0.868292	61.4729	−26.7508	10.5112	0.968657
400	75.8993	−32.5058	21.7799	1.56885	59.9601	−25.9438	11.7438	1.2454
500	73.811	−31.4028	25.1227	2.2557	58.73	−25.2952	13.1377	1.49038
600	72.0975	−30.5057	29.7554	2.87716	57.777	−24.7967	15.199	1.68544
700	70.6838	−29.7709	36.9902	3.43115	57.0145	−24.4006	18.437	1.84803
800	69.501	−29.1598	50.0955	3.92395	56.4023	−24.0844	24.4276	1.98063
900	68.4515	−28.6206	78.9001	4.39787	55.8952	−23.8238	38.8216	2.09124

Table A.8-2 Results of using the ideal values to fit one change point model for all frequencies

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Setup	Broadband,ver,h1=1M,h2=1-4M				Broadband,ver,h1=1.5M,h2=1-4M			
t_m	β_0	β_1	β_2	MSE	β_0	β_1	β_2	MSE
35	44.2328	−18.6395	−0.828288	0.205759	35.1557	−12.4267	−7.40873	0.365433
40	44.5849	−18.8855	−0.588942	0.205654	38.2951	−14.6209	−5.2744	0.357013
45	44.54	−18.8702	−0.616703	0.205356	39.6207	−15.5533	−4.4049	0.348248
50	44.476	−18.8413	−0.661939	0.204883	40.2752	−16.0232	−4.00481	0.338384
60	44.4499	−18.8419	−0.694857	0.20373	41.1747	−16.6538	−3.49939	0.320291
70	44.4277	−18.8414	−0.731087	0.202233	41.6974	−17.0202	−3.24638	0.30287
80	44.395	−18.8328	−0.779671	0.200343	41.9847	−17.2287	−3.15521	0.284093
90	44.3603	−18.8214	−0.834853	0.198102	42.1446	−17.3523	−3.15695	0.26353
100	44.3183	−18.8049	−0.900657	0.195412	42.2405	−17.432	−3.21047	0.241729
120	44.2653	−18.7877	−1.01983	0.189351	42.453	−17.5903	−3.30204	0.201443
125	44.2518	−18.7829	−1.05213	0.18764	42.4976	−17.623	−3.33168	0.191832
140	44.1991	−18.7608	−1.16707	0.181776	42.5848	−17.6906	−3.46636	0.162087
150	44.1664	−18.7471	−1.24719	0.177556	42.6381	−17.7305	−3.56311	0.143542
160	44.1245	−18.7277	−1.3416	0.172756	42.6746	−17.759	−3.67956	0.125549
175	44.0559	−18.6951	−1.49999	0.164721	42.7235	−17.7957	−3.86672	0.101198
180	44.0315	−18.6832	−1.55768	0.161922	42.7433	−17.809	−3.92699	0.0953205
200	43.9248	−18.6297	−1.81605	0.150032	42.8083	−17.851	−4.1917	0.077168
250	43.7224	−18.5288	−2.51015	0.118244	43.0933	−18.0138	−4.72758	0.063833
300	43.6327	−18.4862	−3.21094	0.0902848	43.4775	−18.2231	−5.09255	0.0839166
400	43.7535	−18.5551	−4.46322	0.0669342	44.195	−18.606	−5.72941	0.145715
500	44.0851	−18.7312	−5.52636	0.0790111	44.7946	−18.9222	−6.41148	0.203916
600	44.4373	−18.9158	−6.70265	0.104378	45.2645	−19.1679	−7.38692	0.251393
700	44.7468	−19.0767	−8.43299	0.130704	45.6349	−19.3604	−8.96243	0.289766
800	45.0162	−19.2159	−11.4277	0.156257	45.9394	−19.5176	−11.7103	0.322568
900	45.2503	−19.3362	−18.3953	0.179806	46.1813	−19.6419	−18.7005	0.34773

Table A.8-3 Results of using the ideal values to fit one change point model for all frequencies

Setup	Diploe,hor,h1=2M,h2=1-4M				Dopole,ver,h1=2.75M,h2=2.75-4M			
t_m	β_0	β_1	β_2	*MSE*	β_0	β_1	β_2	*MSE*
35	148.045	−83.9098	60.902	1.58316	41.7092	−15.5094	−5.59517	0.169307
40	117.765	−63.0415	40.4565	1.16847	44.0299	−17.1347	−4.01588	0.164339
45	104.424	−53.9252	31.7337	0.836011	44.9809	−17.8085	−3.39162	0.15891
50	96.8256	−48.7851	26.9748	0.561115	45.4016	−18.1197	−3.1377	0.152301
60	87.0732	−42.3482	21.11	0.228422	46.0774	−18.5965	−2.76103	0.140722
70	81.1095	−38.5053	17.655	0.0838002	46.5506	−18.921	−2.51968	0.131322
80	77.1644	−36.0096	15.4668	0.0307903	46.8779	−19.1424	−2.37484	0.123261
90	74.3356	−34.2506	13.9685	0.0314505	47.1288	−19.309	−2.27996	0.116606
100	72.1875	−32.9362	12.8837	0.0664048	47.3302	−19.4403	−2.21729	0.111164
120	68.9316	−30.9845	11.2548	0.194883	47.7136	−19.6793	−2.08396	0.105578
125	68.3149	−30.6196	10.962	0.228002	47.8368	−19.7518	−2.02208	0.107224
140	66.8194	−29.7436	10.3149	0.324942	48.2647	−19.9955	−1.7656	0.119422
150	66.0137	−29.2773	9.9946	0.388787	48.5059	−20.1309	−1.6136	0.127174
160	65.3605	−28.9024	9.78118	0.446976	48.71	−20.2442	−1.48252	0.134134
175	64.5643	−28.4501	9.58314	0.52759	48.9533	−20.378	−1.32452	0.142487
180	64.3573	−28.3334	9.56451	0.550217	49.0171	−20.4129	−1.28437	0.144693
200	63.7272	−27.9811	9.66266	0.62644	49.2148	−20.5201	−1.16669	0.151527
250	62.4595	−27.2846	10.0323	0.807569	49.5596	−20.7051	−0.939371	0.162302
300	61.4729	−26.7508	10.5112	0.968657	49.7696	−20.8166	−0.781197	0.167733
400	59.9601	−25.9438	11.7438	1.2454	50.0003	−20.9381	−0.569546	0.172312
500	58.73	−25.2952	13.1377	1.49038	50.1186	−20.9999	−0.406985	0.173887
600	57.777	−24.7967	15.199	1.68544	50.1626	−21.0229	−0.378874	0.174251
700	57.0145	−24.4006	18.437	1.84803	50.1775	−21.0306	−0.505909	0.174304
800	56.4023	−24.0844	24.4276	1.98063	50.1878	−21.036	−0.82516	0.174316
900	55.8952	−23.8238	38.8216	2.09124	50.2013	−21.0429	−1.58459	0.174381

Table A.9-1 Maximum bias with one change point model for ideal values

	Broadband,hor,h1=1M,h2=1-4M				Broadband,hor,h1=2M,h2=1-4M			
t_m	$max\ bias$	$\hat{t}_{mb}$	$\lvert relative\ bias \rvert$	$\frac{max\ bias}{\sqrt{MSE_m}}$	$max\ bias$	$\hat{t}_m$	$\lvert relative\ bias \rvert$	$\frac{max\ bias}{\sqrt{MSE_m}}$
35	3.632	35	0.134	1.7894	3.1175	35	0.1443	2.4777
40	3.46	40	0.139	1.8308	2.6309	40	0.1356	2.4339
45	3.2565	45	0.1422	1.8619	2.2258	45	0.1272	2.4343
50	3.0833	50	0.1461	1.9256	1.9588	50	0.1232	2.615
60	2.662	60	0.1479	1.9669	1.3283	60	0.1014	2.7793
70	2.2935	70	0.148	1.9736	0.8365	70	0.0767	2.8896
80	1.8973	80	0.1427	1.9176	0.5652	80	0.0614	3.221
90	1.5682	90	0.1376	1.8973	0.3983	90	0.0511	2.2457
100	1.2625	100	0.1302	1.8874	0.5632	30	0.0234	2.1857
120	0.8686	120	0.1241	2.0402	0.9363	30	0.0389	2.1209
125	0.776	125	0.1212	2.0469	1.0139	30	0.0421	2.1235
140	0.5955	140	0.1241	2.2416	1.2156	30	0.0504	2.1325
150	0.5522	150	0.1416	2.2445	1.3324	30	0.0553	2.1369
160	0.5637	160	0.1818	2.1397	1.4319	30	0.0594	2.1418
175	0.5955	175	0.2978	1.768	1.56	30	0.0647	2.1477
180	0.6597	180	0.388	1.8179	1.5945	30	0.0662	2.1496
200	0.9557	200	1.5928	2.077	1.7042	30	0.0707	2.1532
250	1.6084	250	1.0053	2.2324	1.9432	30	0.0806	2.1624
300	2.1226	300	0.6432	2.2779	2.1413	30	0.0888	2.1756
400	2.7827	400	0.4716	2.2216	2.4621	30	0.1022	2.2062
500	3.0442	500	0.3853	2.0269	2.7341	30	0.1134	2.2396
600	3.152	600	0.3318	1.8583	2.9508	30	0.1224	2.2729
700	3.2173	700	0.2979	1.7369	3.1282	30	0.1298	2.3011
800	3.3715	30	0.1131	1.702	3.2733	30	0.1358	2.3259
900	3.6246	30	0.1216	1.7284	3.3956	30	0.1409	2.3481

(t_{mb} = Corresponding frequency where the max bias occurred,

$relative\ bias = max\ bias / T_{t_{mb}}$ **)**

Table A.9-2 Maximum bias with one change point model for ideal values

	Broadband,ver,h1=1M,h2=1-4M				Broadband,ver,h1=1.5M,h2=1-4M			
t_m	*max bias*	$\hat{t}_{mb}$	$\lvert relative bias \rvert$	$\frac{max bias}{\sqrt{MSE_m}}$	*max bias*	$\hat{t}_m$	$\lvert relative bias \rvert$	$\frac{max bias}{\sqrt{MSE_m}}$
35	1.2123	300	0.8082	2.6726	1.2688	250	4.2294	2.0989
40	1.2122	300	0.8081	2.673	1.2628	250	4.2095	2.1135
45	1.2118	300	0.8079	2.6742	1.2556	250	4.1855	2.1278
50	1.2112	300	0.8075	2.6758	1.2467	250	4.1558	2.1432
60	1.2094	300	0.8063	2.6794	1.2289	250	4.0964	2.1715
70	1.2069	300	0.8046	2.6838	1.2108	250	4.0359	2.2
80	1.2036	300	0.8024	2.6889	1.1901	250	3.9669	2.2327
90	1.1992	300	0.7995	2.6943	1.1659	250	3.8864	2.2712
100	1.1935	300	0.7957	2.7	1.138	250	3.7935	2.3147
120	1.1798	300	0.7866	2.7113	1.08	250	3.6001	2.4064
125	1.1756	300	0.7838	2.714	1.0642	250	3.5472	2.4297
140	1.1601	300	0.7734	2.721	1.0092	250	3.3639	2.5066
150	1.1477	300	0.7651	2.7238	0.9689	250	3.2298	2.5575
160	1.1327	300	0.7551	2.7251	0.9236	250	3.0785	2.6065
175	1.1053	300	0.7369	2.7234	0.8485	250	2.8283	2.6672
180	1.0946	300	0.7297	2.7203	0.8217	250	2.7392	2.6616
200	1.0431	300	0.6954	2.6929	0.7035	250	2.3452	2.5326
250	0.9031	400	0.2203	2.6263	0.4569	200	0.2176	1.8085
300	0.7706	400	0.1879	2.5645	0.5543	200	0.264	1.9135
400	0.7096	300	0.4731	2.7429	0.7811	400	0.1562	2.0462
500	0.8143	300	0.5429	2.8971	0.9243	500	0.1284	2.0468
600	0.9194	300	0.6129	2.8457	0.999	250	3.33	1.9924
700	1.0085	300	0.6724	2.7896	1.09	250	3.6334	2.025
800	1.0839	300	0.7226	2.742	1.1626	250	3.8753	2.047
900	1.1478	300	0.7652	2.7068	1.2187	250	4.0624	2.0667

(t_{mb} = Corresponding frequency where the max bias occurred,

$relative\ bias = max\ bias / T_{t_{mb}}$ **)**

Table A.9-3 Maximum bias with one change point model for ideal values

	Diploe,hor,h1=2M,h2=1-4M				Dopole,ver,h1=2.75M,h2=2.75-4M			
t_m	$max\ bias$	$\hat{t}_{mb}$	$\lvert relative\ bias \rvert$	$\frac{max\ bias}{\sqrt{MSE_m}}$	$max\ bias$	$\hat{t}_m$	$\lvert relative\ bias \rvert$	$\frac{max\ bias}{\sqrt{MSE_m}}$
35	3.1175	35	0.1443	2.4777	1.2058	125	0.1652	2.9305
40	2.6309	40	0.1356	2.4339	1.1873	125	0.1626	2.9289
45	2.2258	45	0.1272	2.4343	1.1668	125	0.1598	2.927
50	1.9588	50	0.1232	2.615	1.1423	125	0.1565	2.9271
60	1.3283	60	0.1014	2.7793	1.098	125	0.1504	2.9269
70	0.8365	70	0.0767	2.8896	1.0594	125	0.1451	2.9235
80	0.5652	80	0.0614	3.221	1.0223	125	0.14	2.9118
90	0.3983	90	0.0511	2.2457	0.9858	125	0.135	2.887
100	0.5632	30	0.0234	2.1857	0.9493	125	0.13	2.8473
120	0.9363	30	0.0389	2.1209	0.8891	125	0.1218	2.7362
125	1.0139	30	0.0421	2.1235	0.8809	125	0.1207	2.6902
140	1.2156	30	0.0504	2.1325	0.9641	125	0.1321	2.79
150	1.3324	30	0.0553	2.1369	1.0068	125	0.1379	2.8232
160	1.4319	30	0.0594	2.1418	1.0403	125	0.1425	2.8404
175	1.56	30	0.0647	2.1477	1.0776	125	0.1476	2.8549
180	1.5945	30	0.0662	2.1496	1.0869	125	0.1489	2.8574
200	1.7042	30	0.0707	2.1532	1.114	125	0.1526	2.8618
250	1.9432	30	0.0806	2.1624	1.157	125	0.1585	2.872
300	2.1413	30	0.0888	2.1756	1.181	125	0.1618	2.8836
400	2.4621	30	0.1022	2.2062	1.2051	125	0.1651	2.9031
500	2.7341	30	0.1134	2.2396	1.2164	125	0.1666	2.9171
600	2.9508	30	0.1224	2.2729	1.2205	125	0.1672	2.9237
700	3.1282	30	0.1298	2.3011	1.2218	125	0.1674	2.9266
800	3.2733	30	0.1358	2.3259	1.2228	125	0.1675	2.9287
900	3.3956	30	0.1409	2.3481	1.2238	125	0.1676	2.9307

(t_{mb} = Corresponding frequency where the max bias occurred,

$relative\ bias = max\ bias / T_{t_{mb}}$ **)**