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Characterization of the Antenna Calibration Test Site (CALTS) of the National Center for Metrology (CENAM) of Mexico

Validation performed according to the CISPR 16-1-5 (2012) international standard

Thesis for the degree of Master of Science in Wireless and Photonics Engineering

ANA MYRIAM URIBE LEAL

Department of Microtechnology and Nanoscience
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2013

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Department of Microtechnology and Nanoscience
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone +46 (0)31-772-1000

Cover:
Picture of the Antenna Calibration Test Site at the National Center for Metrology of Mexico.

This report is written in LaTeX

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Abstract

This project exposes an exhaustive procedure to validate the open-area Antenna Calibration Test Site (CALTS) at the National Center for Metrology (CENAM) of Mexico. It is based on the requirements of the international standard CISPR 16-1-5 edition 2012. The procedure presented here gives a wider characterization of the CALTS performance by measuring at 9 different locations with 3 m separation from each other in the ground plane.

The validation was performed with four standard dipole antennas horizontally polarized resonant at 60 MHz, 180 MHz, 400 MHz, and 700 MHz to cover the frequency range from 30 MHz to 1 GHz. A 10 m distance between the transmitting and receiving antennas was employed. The measured results showed that the criteria of the *site attenuation* and the *receiving antenna height for maximum site attenuation* were met at the frequencies and heights specified by the standard at the 9 locations. Two optimum locations were found for future antenna calibration services and the performance of the CALTS was found to be uniform across the ground plane.

Keywords: antenna calibration, CALTS, CENAM, CISPR 16-1-5, site attenuation, site sectoring

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Contents

Acronyms

AF	Antenna Factor
AG	Antenna Gain
ANSI	American National Standards Institute
CALTS	Calibration Test Site
CENAM	Centro Nacional de Metrologia
CISPR	Comité International Spécial des Perturbations Radioélectrique
EMC	Electromagnetic Compatibility
NEC	Numerical Electromagnetic Code
NMI	National Measurements Institute
PDF	Probability Density Function
SA	Site Attenuation
SC	Sensitivity Coefficient
SSM	Standard Site Method
TEM	Transverse Electro-Magnetic
U	Uncertainty
VNA	Vector Network Analyzer

Chapter 1

Introduction

Open-area calibration test sites (CALTS) are used to calibrate horizontally polarized antennas with an operation frequency from 30 MHz to 1 GHz. To be consider a CALTS, the sites have to be validated according to an international standard called *CISPR 16-1-5: Specification for radio disturbance and immunity measuring apparatus and methods* [1].

Antenna calibration services can also be performed at alternative sites like anechoic chambers, transverse electromagnetic cells (TEM), etc. However, any measurements performed at any of these alternative sites have to be related to those performed in a validated open-area CALTS.

CISPR 16-1-5 specifies the guidelines and requirements that have to be fulfilled by the CALTS, but it does not specify the characterization methodology, i.e. at which positions the validation has to be performed. Therefore, laboratories that own this type of facilities perform the validation in only one position at the site, usually at the center area. By definition a CALTS has to be an uniform area and evaluating for only one position provides a narrow performance information of the CALTS. In a worst case scenario it could lead to a wrong antenna calibration service if, for any reason, the site's performance is not uniform across the ground plane.

1.1 The National Center for Metrology

The National Center for Metrology (CENAM) is the National Measurements Institute (NMI) of Mexico. It is in charge of the establishment and maintenance of measurement standards and provides specialized equipment calibration services. Metrology institutes with similar activities around the world are the NIST in the United States, the NPL in the UK, the PTB in Germany, the SP Technical Research Institute in Sweden, among others.

The Antenna and Electromagnetic Fields Laboratory of CENAM develops and supports national measurement standards such as the Site Attenuation (SA), Antenna Factor (AF), and Antenna Gain (AG). They provide the most reliable reference in Mexico to support calibration of electromagnetic compatibility (EMC) measurements, calibration of communications antennas and validation of other site's facilities. [2]

The CALTS at the CENAM, Figures 1.1 and 1.2, was constructed in 2006. It is an open-area ground plane facility with high quality metrology characteristics. It has dimensions of 30 m × 60 m and it is surrounded by at least 30 m obstacle free zone. The facility includes two antenna masts, connecting cables, and measurement equipment such as spectrum analyzer, RF signal generator, network analyzer, power meter, and auxiliary equipment.

Figure 1.1: CENAM's Open-air Antenna Calibration Test Site

The former validation of the CALTS was performed in 2008 and it was done only at one position on the ground plane as described in [3].

Figure 1.2: CENAM's Antenna Laboratory Building

1.2 Scope

The purpose of this thesis is to provide a broader characterization of the CALTS at the CENAM by evaluating the performance of the site at 9 different locations over the ground plane. Optimum testing points are identified for future antenna calibration services. The validation is based on two criteria: the *site attenuation* and the *receiver antenna height for maximum site attenuation*.

Chapter 2 begins with the theoretical background of the validation requirements established by the standard [1]. Chapter 3 deals with the measuring method and testing set up. Chapter 4 deals with the measured results and the calculations performed to verify the validation process. Finally, Chapter 5 deals with the conclusions derived from the measured results.

Chapter 2

Theoretical Background

Antenna calibration services are based on a measurement called site attenuation (SA). A CALTS has to sufficiently meet the properties that are assumed in SA calculations [1]:

1. A perfectly flat and infinite ground plane
2. Equal amplitude for the incident and reflected waves i.e. a reflection coefficient of $r = 1$
3. A phase difference of $\phi = \pi$ between the incident and reflected waves
4. Negligible influence from the equipment and surroundings of the ground plane

There are three criteria specified in the *CISPR 16-1-5* standard [1] to validate the CALTS, where at least 2 of 3 must be tested and complied. In this project the *Site Attenuation Validation Criterion* and the *Receiving Antenna Height Criterion* are tested.

2.1 Site Attenuation

The site attenuation (SA) defined by the *ANSI 63.5-2006* [4], measures the transmission path loss between a receiving and transmitting antenna in an open site with a specific polarization, separation and height.

The SA can be calculated by using a network model where the site is represented as a t-network, Figure 2.1. [1]

The numerical model used for the calculation of the site attenuation is called the *method of moments*. It consists of two wires of 31 segments above an infinite and perfectly conducting ground plane. The wire that represents

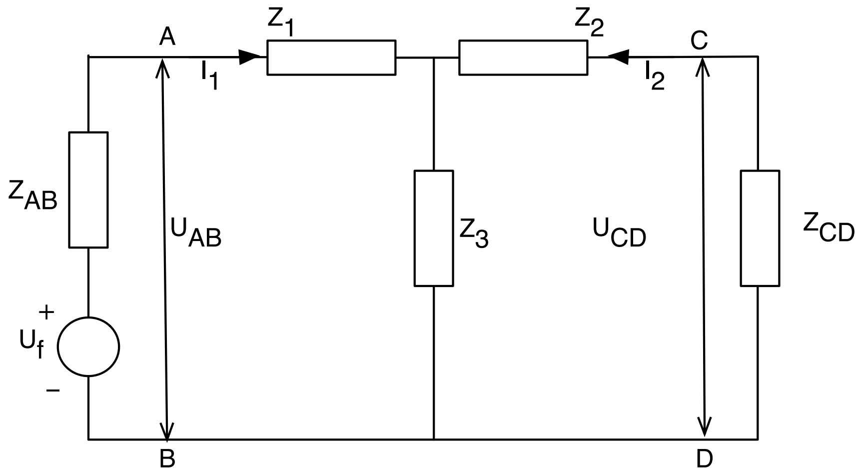


Figure 2.1: Equivalent Network model for SA calculations

the transmitting antenna is centered and fed with a voltage of $U_f = 1 + j0$. The wire that represents the receiving antenna is loaded with an impedance equal to Z_{CD} that is the equivalent impedance of the BALUN and connecting cable of the antenna. The SA is defined by [1]

$$SA_c = 20\log_{10}\left\{\frac{U_f}{|I_2|}\left|\frac{Z_a + Z_{AB}}{Z_a(Z_{AB}+Z_{CD})}\right|\right\}, \tag{2.1}$$

where I_2 is the load current, Z_a is the input impedance of the transmitting antenna, Z_{AB} is the equivalent impedance of the BALUN, connecting cable of the transmitting antenna and generator, Z_{CD} is the equivalent impedance of the BALUN, and connecting cable of the receiving antenna. [1]

2.2 Uncertainty and Tolerances

In all measurements there is a natural imperfection that makes it impossible to quantify with absolute confidence the true magnitude value of the measurement. This error is known as *uncertainty*. [5].

The *ISO/IEC 17025*, [6] is an international standard that specifies the general requirements that testing and calibration laboratories have to follow. The laboratories have to report an estimation of the uncertainty of the measurements for all their services. The guideline used for the uncertainty calculation is the *Guide to the Expression of Uncertainty Measurements*, [5].

The associated uncertainty of the measurements depends on several factors such as the equipment, the system set-up, the methods, and even in some cases the personnel skills.

The calculation begins by identifying the uncertainty sources. Each uncertainty source is then quantified depending on the behavior of the data and it is associated to a probability distribution. There are two methods to quantify the uncertainty sources: Type A and Type B. Type A is for data that is obtained from measuring in a controlled environment with repeatability conditions. The standard uncertainty of the mean value is given by, [7]

$$u(x) = \frac{s_p}{\sqrt{n}}, \tag{2.2}$$

where s_p is the mean measured value, and n is the number of samples taken. The ideal number of samples depends on the requirements of each measurement, as the number increases there is reduction of the measured uncertainty proportional to $1/\sqrt{n}$, [7]. The standard uncertainty also depends on the probability distribution. For a normal distribution the uncertainty, U, is given by

$$U = k \cdot u(x), \tag{2.3}$$

where k is the coverture factor for a specific confidence level. In a normal distribution the confidence level is related to a parameter that establishes the limits of the confidence called, ν, degrees of freedom. As ν increases, the confidence level increases, [7]. For a rectangular distribution the standard uncertainty is given by

$$u(x) = \frac{\sigma}{\sqrt{12}}, \tag{2.4}$$

where σ is the standard deviation of s_p. Type B is for data that is obtained from previous experience like calibration certificates, service manuals, etc. The standard uncertainty for this type also depends on the probability distribution, [7]. For a rectangular distribution the standard uncertainty is given by

$$u(x) = \frac{\sigma}{\sqrt{3}}. \tag{2.5}$$

Then, the values $u(x)$ are combined with a sensitivity coefficient to reflect the impact of each uncertainty source, [7]. This combination is named $u(y)$.

$$u(y) = c \cdot u(x), \tag{2.6}$$

where c is the sensitivity coefficient. Finally, all the values are added in a geometric sum and the final calculated uncertainty value, U, is obtained. [7]

The data can be represented in any form but the one used in the this project will be represented like in Table 2.1. The table shows the uncertainty sources, the expected value of the uncertainty sources (EV), the probability distribution (PDF), the standard uncertainty $u(x)$, the sensitivity coefficients (SC), the uncertainty contribution $u(y)$, the degrees of freedom ν, the combined uncertainty (U_c), the effective degrees of freedom ν_{eff}, the coverture factor k for a confidence level $\rho = 95\%$ and the expanded and final value of the estimated uncertainty (U).

Table 2.1: Uncertainty Calculation

Uncertainty Source	**EV** [dB]	**PDF**	**u(x)** [dB]	**SC**	**u(y)** [dB]	ν
Source a	X	Norm/ Rect	X	X	X	X
Source b	X	Norm/ Rect	X	X	X	X
Source c ...	X	Norm/ Rect	X	X	X	X
U_c **[dB]**	X					
ν_{eff}	X					
k, $\rho = 95\%$	X					
U [dB]	X					

A *tolerance* is not the same as an uncertainty. The uncertainty is related to a measurement result whereas a tolerance is a limit fixed or designated by a standard. For example the maximum tolerances for various parameters specified by the CISPR 16-1-5 [1] are in Table 2.2 and Figure 2.2. If these tolerances are met, then an uncertainty contribution from Table 2.2 can be included in the uncertainty calculation.

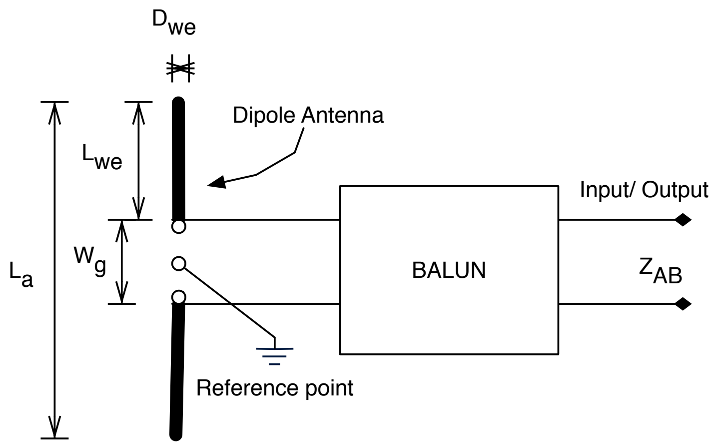


Figure 2.2: Schematic of the Test Antenna and BALUN

Table 2.2: Maximum Tolerances

Variable	Description	Maximum Tolerance
L_a	Longitude between the edge elements of the antenna	$\pm$ 0.00025 L_a or $\pm$ 0.001 (m) if L_a $<$ 0.004 (m)
Z_{AB}	Specified impedance at the BALUN output	VSWR $\leq$ 1.10
A_b	Balance amplitude	$\pm$ 0.4 dB
ϕ_b	Balance phase	$\pm$ 2°
d	Horizontal distance between antenna centers	$\pm$ 0.04 m
h_t	Tx antenna height	$\pm$ 0.01 m
h_r	Rx antenna height	$\pm$ 0.01 m
f	Testing frequency	$\pm$ 0.001f

2.3 Antenna Specifications

The requirements for the test antenna used for the SA measurement are specified by the *CISPR 16-1-5* standard [1]. The test antenna consist of a BALUN and two colinear wire elements. The normative specifications for the test antenna are as follows [1]:

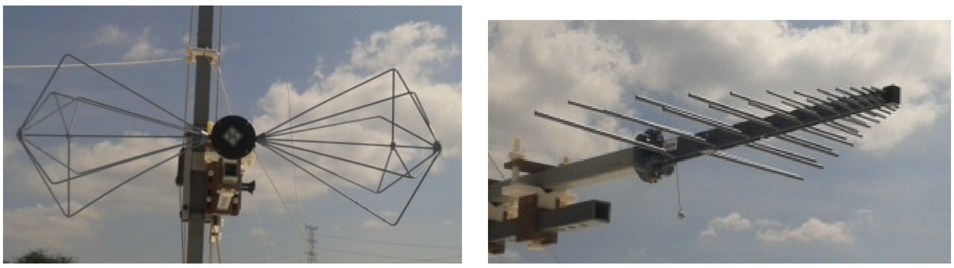
1. The test antenna shall have identical wire elements of length L_{WE}.
2. The total length L_a shall be of approximately $\lambda/2$ at the operation frequency f and shall have an input impedance of less than 1 Ω at the feed terminals.
3. The gap W_g shall be less than 15 mm or less than $0.03\lambda_{min}$. $\lambda_{min} = c_0/f_{max}$ where f_{max} is the highest test frequency at which the antenna is employed.
4. The length L_a is within the tolerance given by Table 2.2.
5. The balance port of the BALUN shall have a specified impedance Z_{AB}, and an amplitude balance and phase balance as specified by Table 2.2 when both feed terminals are terminated in an impedance of $Z_{AB}/2$.
6. The BALUN properties can be determined from s-parameters measurements.
7. If the test antennas or equipment have a matching impedance different from 50 Ω or 100 Ω it should be explicitly mentioned in the report.

Chapter 3

Methodology

3.1 Ambient Noise Measurement

The surrounding environment of the CALTS could affect the measurements if there were any noise signal located at the testing frequencies in the range from 30 MHz to 1 GHz. This condition was evaluated as follows. The measurement was performed with a spectrum analyzer HP8566B. Broadband antennas were preferred for the test to minimized the number of measurements. At the CENAM the available broadband antennas, Figure 3.1, were a biconical dipole, with an operational frequency range from 30 MHz to 300 MHz, and a logarithmic periodical antenna, with an operational frequency range from 200 MHz to 1 GHz.



a) *b)*

Figure 3.1: Broadband Antennas a) Biconical Dipole; b) Logarithmic Periodical

3.2 Site Attenuation Validation Criterion

The Site Attenuation Validation Criterion, [1], states that:

$$|SA_c[dB] - SA_m[dB]| \leq T_{SA}[dB] - \Delta SA_m[dB], \qquad (3.1)$$

where SA_c is the theoretical site attenuation, SA_m is the measured site attenuation, T_{SA} is the tolerance with a 1 dB value stated by the *CISPR 16-1-5* standard [1], and ΔSA_m is the uncertainty of the measured site attenuation expressed with a 95% confidence level.

This criterion was tested at 24 frequencies, f, and receiver antenna heights, h_r, specified in Table 3.1 and a fixed transmitter antenna height, $h_t = 2$ m.

Table 3.1: Testing Requirements of SA Criterion

Dipole [MHz]	f **[MHz]**	h_r **[m]**	**Dipole [MHz]**	f **[MHz]**	h_r **[m]**
60	30	4	180	160	2
	35	4		180	2
	40	4		200	2
	45	4		250	1.5
	50	4	400	300	1.5
	60	4		400	1.2
	70	4		500	2.3
	80	4	700	600	2
	90	4		700	1.7
	100	4		800	1.5
180	120	4		900	1.3
	140	2		1000	1.2

Dipole antennas are used because the validation process requires test antennas that can be accurately modeled.

The testing procedure of the criterion, [1], was as follows:

1. **Reference mode** - First, a direct connection was set between the receiver and transmitter sources via cables, attenuators, as necessary, and a straight through adapter, as shown in Figure 3.2a. The signal was denoted U_{r1}.

2. **Antenna-to-antenna mode** - Then, the reference mode was opened and a pair of receiving and transmitting antennas were connected to their signal source and measurement equipment, as shown in Figure

3.2b. The transmitting antenna was fixed at a height of 2 m. The receiving antenna was set at the heights specified by Table 3.1, The maximum signal was denoted U_s.

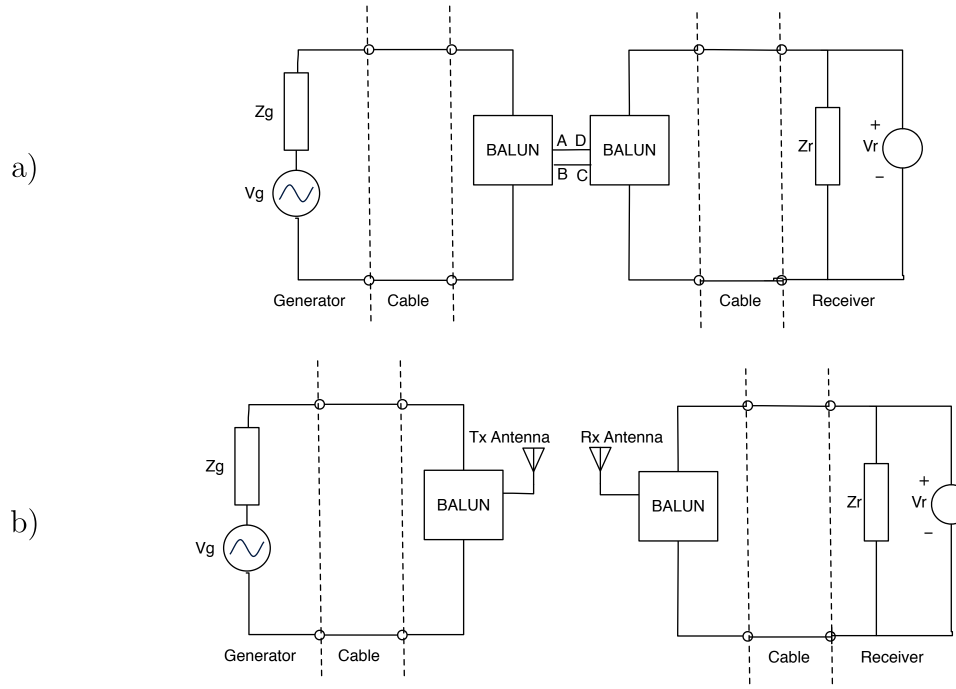


Figure 3.2: a) Reference/Direct Mode, b) Antenna-to-antenna Mode

3. **Direct-connection mode** - Then, the antennas were removed and a direct connection was set again. The signal was denoted as U_{r2}.

4. If a difference of more than 0.2 dB between U_{r1} and U_{r2} was detected the value was considered as unstable or drifting and the procedure was repeated.

5. The site attenuation was calculated as

$$SA_{dB} = U_{ra,dB} - U_{s,dB}, \tag{3.2}$$

where U_{ra} is the average between U_{r1} and U_{r2}.

3.3 Receiving Antenna Height Criterion

The Receiving Antenna Height Criterion, [1], states that:

$$|h_{rc}[m] - h_{r,max}[m]| \leq T_{hr}[m] - \Delta h_{rm}[m], \tag{3.3}$$

where h_{rc} is the theoretical height that gives the maximum SA, $h_{r,max}$ is the measured height that gives the maximum SA, T_{rm} is the tolerance with a 0.05 m value stated by the *CISPR 16-1-5* standard [1], and Δh_{rm} is the measured height uncertainty with a 95% confidence level.

The aim of this method was to find the receiving antenna height at which the site attenuation shown the first maximum peak. At the maximum SA there is a near total cancellation of the direct wave that arrives at the receiver antenna with the reflected wave from the ground plane.

The antenna height scan measurement was performed at the three frequencies specified in Table 3.2.

Table 3.2: Requirement for Height Criterion

Dipole **[MHz]**	f [MHz]
300	300
600	600
900	900

The measuring method to test this criterion was done by increasing the height of the receiver antenna from 1 m till $h_{r_{max}}$ that gave the first sharp maximum in the site attenuation reading. The value of the receiver reading is not of interest, it is only used to find the height value.

3.4 Theoretical Values Calculation

The theoretical site attenuation and receiver antenna height values were calculated with the aid of a software called *AS_CENAM.vee* developed at CENAM and programmed in HP VEE. The software implements (2.1). The computer program is based on a freeware open-source software called Numerical Electromagnetic Code (NEC).

NEC simulates the dipole antennas as straight wires divided into 31 segments as recommended, [1]. The input data such as wire diameter, wire lengths, operation frequency, height and separation distance are specified by the user. The wire diameter and wire length of the dipole antennas are specified in [3]. The theoretical site attenuation values were calculated by setting the frequencies and heights specified in Table 3.1. The theoretical receiver antenna heights were calculated varying the height from 1 m to 4 m with steps of 1 cm at the specified frequencies in Table 3.2.

3.5 CALTS Sectoring and Testing Points

The site area was divided into a grid and a combination of 9 locations was selected for the measurements. The number of locations was decided based on the time from 2008 validation, [3], and the available time for this project. An average of all measurements provided an improved characterization of the site and identified optimum locations for future antenna calibration services.

A 10 m separation between the transmitter and receiver antenna was used as stated by the *CISPR 16-1-5* standard [1]. The chosen separation between locations was 3 m, Figure 3.3.

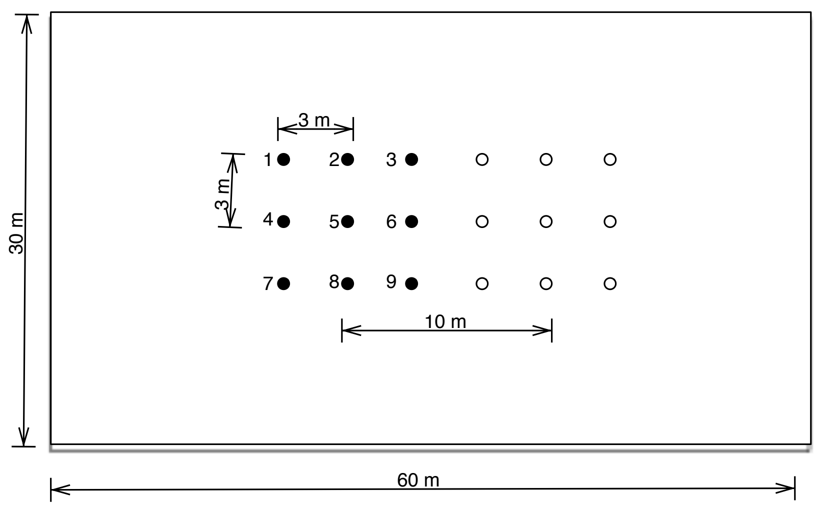


Figure 3.3: CALTS Sectoring. Dimensions are not to scale

3.6 Test Set-up

The system setup is shown in Figure 3.4. The set up is automatized and it only requires to manually connect the antennas. The positioning mast unit of the receiver antenna and the vector network analyzer (VNA) HP8714ES are remotely controlled by a computer software. To ensure the stability of the tested frequency, the VNA requires a 10 MHz reference clock signal supplied by a spectrum analyzer HP8566B whose reference clock signal is locked to a master crystal oscillator HP105B. The transmitter mast is moved manually since it is set at a fixed height.

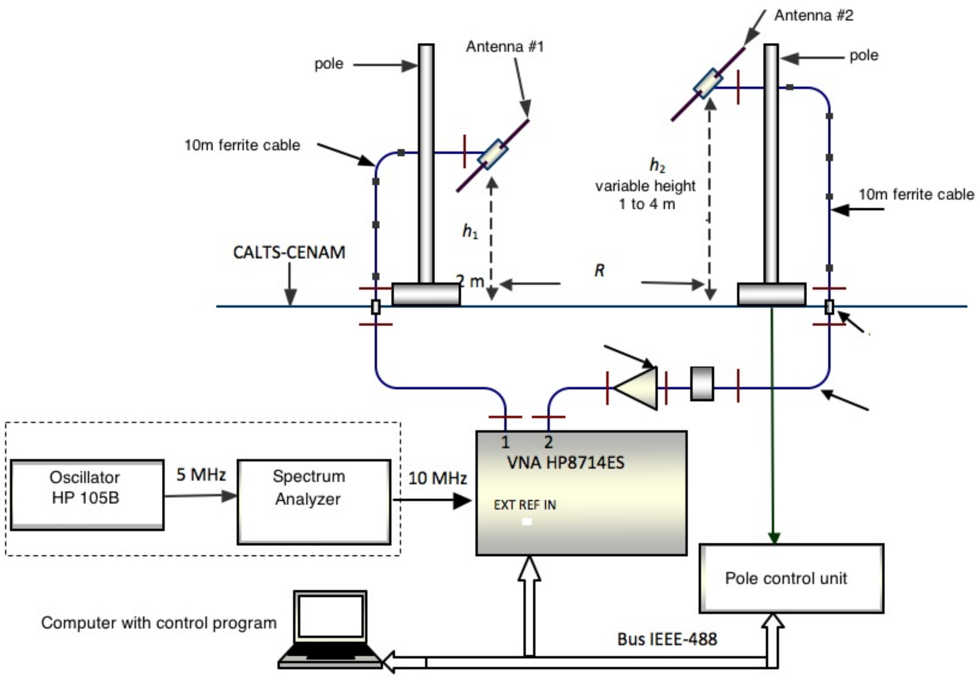


Figure 3.4: System employed to measure SA [1]

The software takes the measurement readings at the frequencies and heights specified by Tables 3.1 and 3.2. It was decided to take 7 readings at each frequency point for the site attenuation criterion measurement. This number of readings gave a measuring average time of 5 minutes for each frequency. Although more readings could have be taken the recording of the measurements in this process is slow and the waiting time would have been longer. A mean value of the 7 readings and an associated standard deviation was calculated for each frequency. The calculated standard deviation of the measurement readings was used for the uncertainty calculation.

The control equipment at the base of the mast is metallic and it is an undesired reflecting object for signals. This can be an issue especially at high frequencies. To avoid it, pieces of absorber material, Figure 3.5, were placed over the control equipment of the masts when (3.1) was not met without them.

[1]Image courtesy of Israel Garcia

Figure 3.5: RF absorber material

CENAM developed three sets of 24 resonant dipoles and they comply with the normative specifications of Section 2.3. Details of the construction and dimensions of these antennas can be consulted in [3]. Figure 3.6 shows the antenna pairs used for 60 MHz, 180 MHz, 400 MHz and 700 MHz. These antennas are fully calculable standards. The antennas are connected through the use of commercial BALUNs, Figure 3.7.

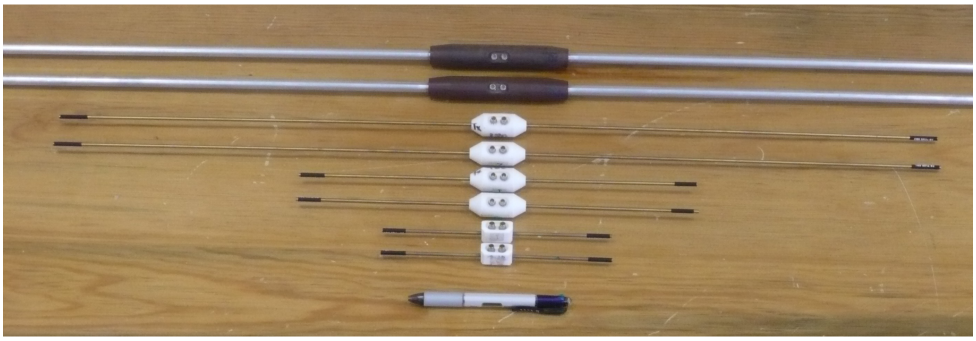


Figure 3.6: Dipoles of 60 MHz, 180 MHz, 400 MHz and 700 MHz

The method described in Section 3.2 was implemented for the site attenuation measurements. At all the locations a direct mode and antenna-to-antenna mode were tested, Figures 3.8 and 3.9. The method described in Section 3.3 was implemented for the heigh criterion measurements.

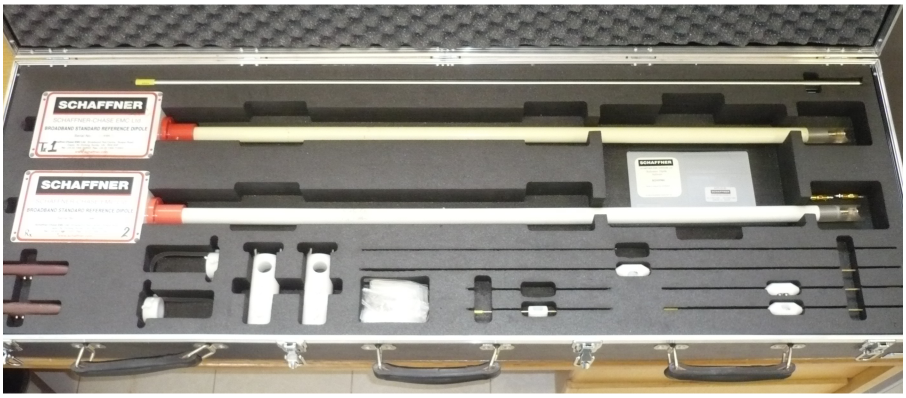


Figure 3.7: Schaffner BALUNs equipment

Figure 3.8: Direct Mode

Figure 3.9: Antenna-to-Antenna Mode

Chapter 4

Results

4.1 Ambient Noise Measurement

The noise power was measured at both the transmitter and receiver positions. Below 300 MHz the broadband antenna in Figure 3.1a was employed and above 300 MHz the broadband antenna of Figure 3.1b was employed. Figures 4.1 and 4.2 show that all the signals values are around -95 dBm. It can be concluded that for all the frequency range from 30 MHz to 1 GHz there was not any noise signal interfering with the site attenuation and height measurements.

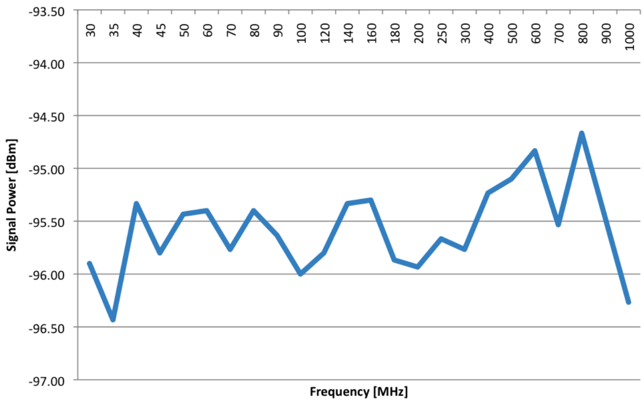


Figure 4.1: Measured Ambient Noise at the Receiving Position

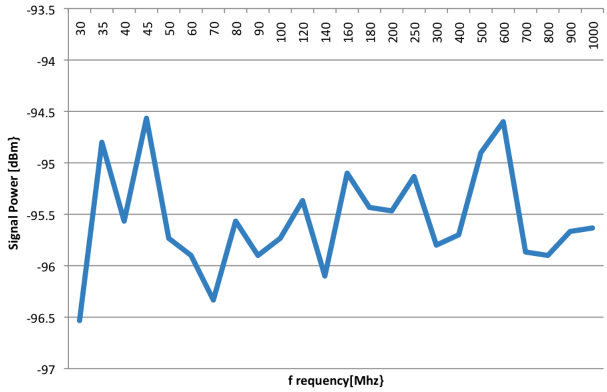


Figure 4.2: Measured Ambient Noise from the Transmitting Position

4.2 Site Attenuation Criterion

4.2.1 Theoretical SA

The obtained results of the site attenuation for 4 dipole antennas with the receiving antenna heights specified in Table 3.1, a transmitter antenna height of 2 m, and separation distance of 10 m between transmitting and receiving antennas are shown in Table 4.1.

Table 4.1: Theoretical Site Attenuation for 4 Dipoles

Dipole [MHz]	f **[MHz]**	h_r **[m]**	SA_c **[dB]**	**Dipole [MHz]**	f **[MHz]**	h_r **[m]**	SA_c **[dB]**
60	30	4	55.10	180	160	2	30.77
	35	4	48.34		180	2	27.56
	40	4	41.97		200	2	30.93
	45	4	35.63		250	1.5	38.90
	50	4	29.33	400	300	1.5	45.51
	60	4	22.02		400	1.2	34.78
	70	4	24.43		500	2.3	40.48
	80	4	28.37	700	600	2	42.07
	90	4	31.61		700	1.7	39.54
	100	4	33.18		800	1.5	41.96
180	120	4	46.68		900	1.3	44.70
	140	2	40.36		1000	1.2	45.11

4.2.2 SA Measurement

The 9 locations of Figure 3.3 were tested and Table 4.2 shows the measured site attenuation at each one. Locations 4 and 5 showed to have the closest measured values to the theoretical ones. A more detailed analysis of the measurements and the environmental conditions under which the tests were performed can be found in Appendix A.

Table 4.2: Measure Site Attenuation at the 9 Locations

f **[MHz]**	SA_{m1} **[dB]**	SA_{m2} **[dB]**	SA_{m3} **[dB]**	SA_{m4} **[dB]**	SA_{m5} **[dB]**	SA_{m6} **[dB]**	SA_{m7} **[dB]**	SA_{m8} **[dB]**	SA_{m9} **[dB]**
30	55.56	55.56	55.58	55.68	55.70	55.69	55.51	55.70	55.68
35	47.84	47.77	47.92	47.85	47.83	47.80	47.85	47.80	47.94
40	42.46	42.47	42.52	42.64	42.49	42.59	42.44	42.64	42.61
45	35.52	35.46	35.57	35.32	35.53	35.26	35.55	35.32	35.42
50	29.65	29.62	29.69	29.73	29.70	29.71	29.63	29.80	29.83
55	21.99	21.98	22.01	22.05	22.01	22.02	21.96	22.02	22.05
60	24.13	24.22	24.18	24.24	24.29	24.20	24.14	24.15	24.15
70	27.89	27.98	27.82	28.11	28.10	28.09	27.81	28.12	28.02
80	31.08	31.25	31.12	31.25	31.33	31.19	31.10	31.16	31.11
90	32.65	32.79	32.65	32.84	32.90	32.80	32.67	32.78	32.74
100	46.19	46.39	46.24	46.35	46.42	46.41	46.27	46.56	46.28
20	40.02	40.04	40.09	40.08	39.93	40.01	40.10	39.90	39.82
160	30.27	30.29	30.42	30.50	30.32	30.32	30.33	30.33	30.50
180	27.56	27.60	27.68	27.65	27.57	27.57	27.67	27.24	27.70
200	30.96	31.01	30.81	30.97	30.99	30.98	30.59	31.45	30.98
250	38.78	38.94	38.69	39.03	38.92	38.76	38.45	39.44	38.78
300	44.82	45.01	44.95	45.18	45.18	44.83	44.74	45.21	44.82
400	34.63	35.38	34.65	34.95	34.98	34.91	34.60	34.96	35.04
500	40.59	40.24	40.87	40.62	40.28	40.87	40.31	40.43	40.58
600	41.75	41.49	42.04	42.54	41.93	41.02	41.89	42.03	41.83
700	39.48	39.40	39.03	39.98	39.22	40.53	40.04	38.91	39.89
800	42.65	42.08	42.38	41.92	41.65	41.39	42.41	42.35	42.28
900	46.33	44.25	46.68	44.60	44.29	43.39	44.41	44.47	44.21
1000	48.07	46.17	47.86	47.88	48.04	46.67	48.10	46.65	49.81

4.2.3 SA Uncertainty Estimation

As explained before, the uncertainty depends on the system employed for the measurement. In this case, the uncertainty sources for the site attenuation measurement are those related to the measurement of U_{r1}, U_{r2} and U_s and how accurately the tolerance conditions from Table 2.2 were followed or met.

With the automated measurement system, 7 readings were taken for U_{r1}, U_{r2} and U_s at each tested frequency. The vector network analyzer HP8714ES has a 0.01 dB resolution and linearity of 0.02 dB [8]. Table 4.3 shows the uncertainty calculation. The obtained 0.32 dB for the uncertainty is well inside the expected values as stated by the *CISPR 16-1-5* standard.

Table 4.3: Theoretical Site Attenuation Uncertainty

Uncertainty Source	**EV** [dB]	**PDF**	**u(x)** [dB]	**SC**	**u(y)** [dB]	ν
U_{direct} deviation		Normal	0.00	1	0.00	6
U_{direct} resolution	0.01	Rectangular	0.00	1	0.00	60
$U_{ant-ant}$ deviation		Normal	0.00	-1	0.00	6
$U_{ant-ant}$ resolution	0.01	Rectangular	0.01	-1	0.00	60
VNA Receiver linearity	0.20	Rectangular	0.12	1	0.12	60
Tolerance from Table 2.2	0.20	Rectangular	0.12	1	0.12	60
U_c **[dB]**	0.16					
ν_{eff}	120					
k, $\rho = 95\%$	1.96					
ΔSA_m **[dB]**	**0.32**					

4.2.4 SA Compliance Calculation

An average measured site attenuation, SA_m, was calculated to evaluate the criterion specified by (3.1). It is shown in Table 4.4 and Figure 4.3 that the criterion is met at all frequencies.

Table 4.4: Site Attenuation Compliance Calculation

Dipole [MHz]	f [MHz]	h_r [m]	SA_c [dB]	SA_m [dB]	ΔSA_m [dB]	$\mid SA_c - SA_m \mid$ [dB]	$T_{SA} - \Delta SA_m$ [dB]
60	30	4	55.10	55.63	0.32	0.52	0.68
	35	4	48.34	47.85	0.32	0.49	0.68
	40	4	41.97	42.52	0.32	0.56	0.68
	45	4	35.63	35.46	0.32	0.16	0.68
	50	4	29.33	29.70	0.32	0.37	0.68
	60	4	22.02	22.01	0.32	0.02	0.68
	70	4	24.43	24.20	0.32	0.24	0.68
	80	4	28.37	28.00	0.32	0.37	0.68
	90	4	31.61	31.19	0.32	0.42	0.68
	100	4	33.18	32.77	0.32	0.42	0.68
180	120	4	46.68	46.35	0.32	0.33	0.68
	140	2	40.36	39.98	0.32	0.37	0.68
	160	2	30.77	30.35	0.32	0.42	0.68
	180	2	27.56	27.58	0.32	0.02	0.68
	200	2	30.93	30.98	0.32	0.04	0.68
	250	1.5	38.90	38.86	0.32	0.04	0.68
400	300	1.5	45.51	44.97	0.32	0.54	0.68
	400	1.2	34.78	34.90	0.32	0.13	0.68
	500	2.3	40.89	40.50	0.32	0.39	0.68
700	600	2	42.07	41.84	0.32	0.23	0.68
	700	1.7	39.54	39.56	0.32	0.01	0.68
	800	1.5	41.96	42.16	0.32	0.20	0.68
	900	1.3	44.70	44.73	0.32	0.03	0.68
	1000	1.2	47.55	47.69	0.32	0.14	0.68

4.3 Receiver Height Criterion

4.3.1 Theoretical Height

The height with the resulting maximum site attenuation gave the value of h_{rc} as shown in Figure 4.4 and Table 4.5. Details on how these theoretical heights were found for each frequency can be found in Appendix A.

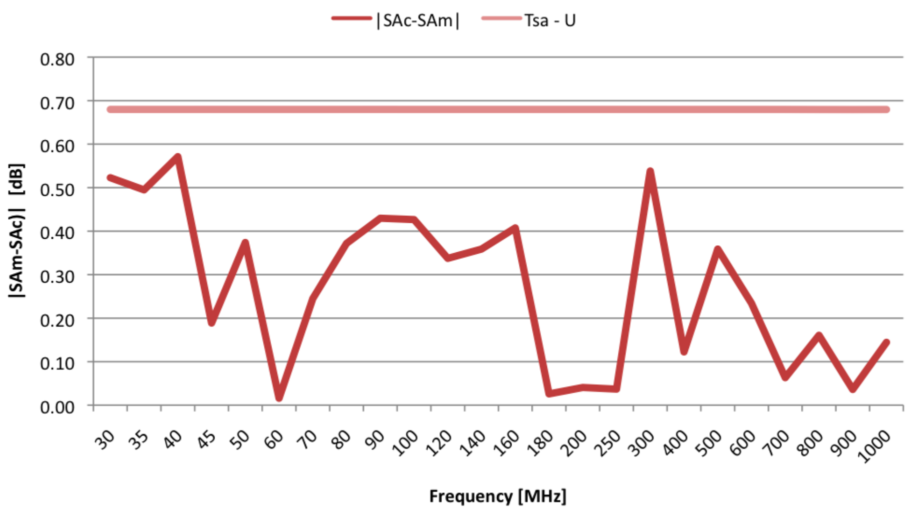


Figure 4.3: Site Attenuation Compliance Criterion

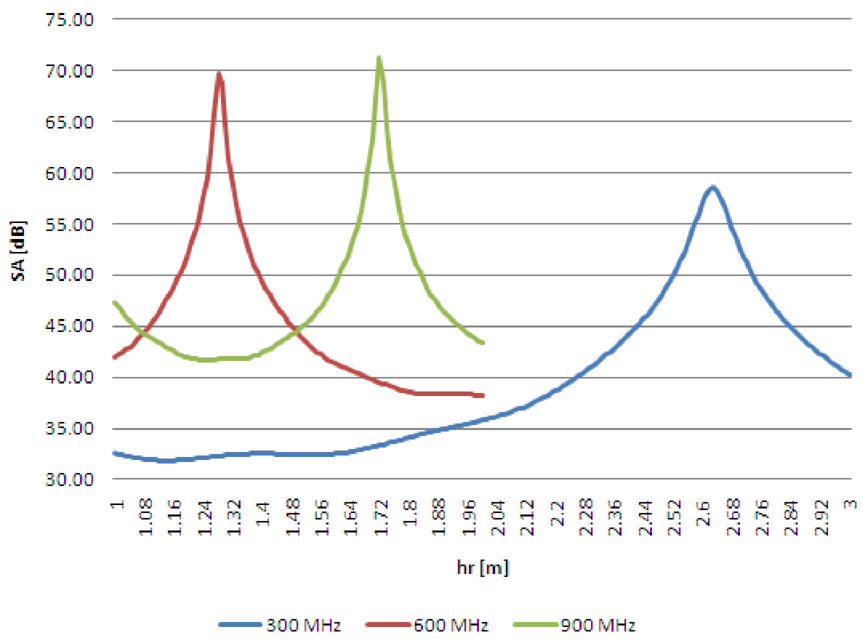


Figure 4.4: Site Attenuation Peaks at 300, 600, and 900 MHz

4.3.2 Height Measurement

Given that the results from the Site Attenuation Criterion showed that the site is uniform, the height measurement was performed only at one location,

Table 4.5: Theoretical Height for Maximum Site Attenuation

Dipole [MHz]	f [MHz]	h_{rc} [m]
300	300	2.63
600	600	1.28
900	900	1.72

number 5 of Figure 3.3. The results are shown in Table 4.6. Details of the measurements and the environmental conditions under which the tests were performed can be found in Appendix A.

Table 4.6: Measured Height for Maximum Site Attenuation

Dipole [MHz]	f [MHz]	h_{rm} [m]
300	300	2.65
600	600	1.31
900	900	1.69

4.3.3 Height Uncertainty Estimation

The measured uncertainty h_{rm}, [1], is given by

$$\Delta h_{rm} = \sqrt{\{\Delta h_{r,max}(m)\}^2 + \{\Delta h_{rt}(m)\}^2}, \quad (4.1)$$

where $\Delta h_{r,max}$ is the associated measurement uncertainty for $h_{r,max}$ and Δh_{rt} is the sensitivity of $h_{r,max}$, $h_{r,max} = 2$ cm if the criteria from Table 2.2 are met.

The uncertainty sources for the height measurements are those related with the measurement of h_r.

With the automated measurement system the receiver antenna height scan was repeated 10 times for each frequency: 300 MHz, 600 MHz, and 900 MHz. The positioning mast unit of the receiving antenna has a resolution of 1 cm [9]. A calibration service, [10], was performed to the mast to find discrepancies between the height given by the positioning control unit reading and the actual height. From that service it was found an associated uncertainty figure of:

$$(\pm 0.24 + 0.003L) \text{ [mm]}, \quad (4.2)$$

where L is the height expressed in m.

The calculated uncertainty is shown in Table 4.7. Given that $\Delta h_{r,max} = \pm 0.01$ m, $\Delta h_{rm} = \pm\ 0.02$ m.

Table 4.7: Theoretical Height Uncertainty

Uncertainty Source	**EV [m]**	**PDF**	**u(x) [m]**	**SC**	**u(y) [m]**	ν
Mast resolution	0.01	Rectangular	0.00	1	0.00	60
Height measurement deviation		Normal	0.00	1	0.00	9
Uncertainty mast error	0.00	Rectangular	0.00	1	0.00	60
U_c **[m]**	0.01					
ν_{eff}	69					
k**,** $\rho = 95\%$	1.96					
$U_{r,max}$ **[m]**	0.01					
Δh_{rm} **[m]**	**0.02**					

4.3.4 Height Compliance Calculation

The measured height was associated with the calculated uncertainty to evaluate the criterion specified by (3.3). In Table 4.8 and Figure 4.5 it can be shown that at the 3 frequencies the criterion is met.

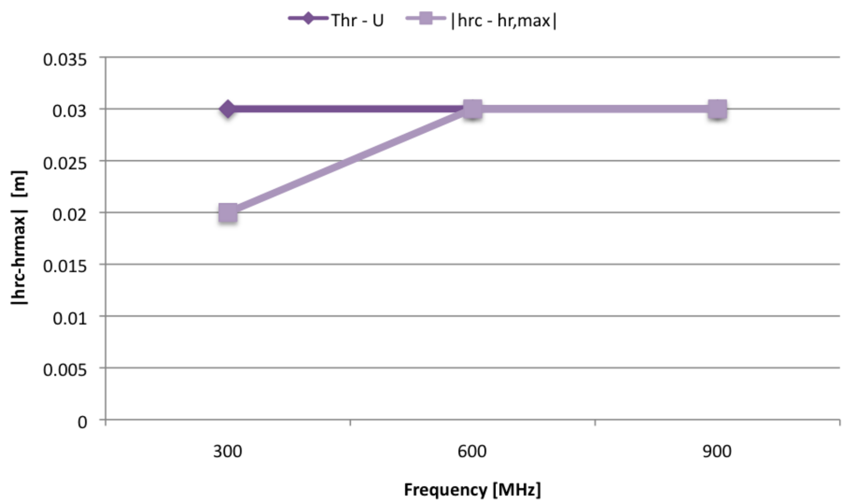


Figure 4.5: Receiver Antenna Height Compliance Criterion

Table 4.8: Receiver Antenna Height Compliance Criterion

Dipole [MHz]	f **[MHz]**	h_{rc} **[m]**	h_{rm} **[m]**	Δh_{rm} **[m]**	$\mid h_{rc} - h_{rm} \mid$ **[m]**	$T_{hr} - \Delta h_{rm}$ **[m]**
300	300	2.63	2.65	0.02	0.02	0.03
600	600	1.28	1.31	0.02	0.03	0.03
900	900	1.72	1.69	0.02	0.03	0.03

Chapter 5

Conclusions and Further Work

The open-area calibration testing site at the CENAM has been validated according to the *CISPR 16-1-5 (2012)* international standard, [1], and complies with the *Site Attenuation Criterion* and the *Receiving Antenna Height Criterion* at the 9 locations specified in Figure 3.3.

The site attenuation criterion was met at the 24 frequencies specified on Table 3.1 using the mean SA measured value at the 9 locations. In some cases the measured SA was lower than the calculated. This discrepancy can be due to the fact the theoretical model takes into account an infinite and perfectly flat ground plane which is not the case in the practice. Also the height used for each frequency is the one stated by the standard but the height for maximum site attenuation may vary for each site. The receiver antenna height for maximum site attenuation for the CALTS at the CENAM was found by the Receiving Antenna Height Criterion.

The height of the receiver antenna for maximum site attenuation criterion was met at the 3 frequencies specified on Table 3.2. It is observed that at 600 and 900 MHz the height values are at the limit of the criterion. The greatest contribution to the height value comes from the uncertainty calculation. Future work can be dedicated to find solutions to decrease the measurement uncertainty.

It can be concluded that the site's behavior is uniform within the tested area and that the placement of the equipment at a specific location is not critical. From the obtained results of the site attenuation measurement locations 4 and 5 gave the closest measured values to the theoretical one and they are considerer as optimal testing positions for future calibration services.

The anticipated validity period of the work presented in this report is of 2 years. The validity period is defined in the quality system established by the Antenna and Electromagnetic Fields Laboratory of CENAM given the environmental exposure of the ground plane, [11]. However, from the results of this validation exercise and the previous one, it is thought that the validity period can be extended from 3 to 4 years if the site is properly maintained from the natural deterioration due to the environmental exposure.

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Appendix A

Data Appendix

Table A.1: Receiver Antenna Measured Height Values

Sample Num.	$h_{r,max}$ 300 MHz **[m]**	$h_{r,max}$ 600 MHz **[m]**	$h_{r,max}$ 900 MHz **[m]**
1	2.65	1.31	1.69
2	2.65	1.31	1.69
3	2.64	1.31	1.69
4	2.65	1.31	1.69
5	2.65	1.32	1.69
6	2.65	1.32	1.69
7	2.65	1.32	1.69
8	2.65	1.31	1.69
9	2.65	1.31	1.69
10	2.65	1.31	1.69
Standard Deviation	0.003	0.005	0.000
Mean value	2.65	1.31	1.69

Table A.2: Measured SA at Locations 1 and 2

Dipole [**MHz**]	f [MHz]	h_r [m]	SA_c [dB]	U_{ra1} [dB]	σ_{Ura1}	U_{s1} [dB]	σ_{Us1}	SA_{m1} [dB]	Abs	U_{ra2} [dB]	σ_{Ura2}	U_{s2} [dB]	σ_{Us2}	SA_{m2} [dB]	Abs
60	30	4	55.10	15.38	0.00	-40.18	0.01	55.56	0	15.56	0.00	-40.01	0.01	55.56	0
	35	4	48.34	15.59	0.00	-32.25	0.01	47.84	0	15.45	0.00	-32.32	0.01	47.77	0
	40	4	41.97	14.51	0.00	-27.95	0.00	42.46	0	14.58	0.00	-27.89	0.01	42.47	0
	45	4	35.63	14.77	0.00	-20.75	0.00	35.52	0	14.73	0.00	-20.74	0.00	35.46	0
	50	4	29.33	14.21	0.00	-15.45	0.00	29.65	0	14.07	0.00	-15.55	0.00	29.62	0
	60	4	22.02	14.16	0.00	-7.82	0.00	21.99	0	14.04	0.00	-7.95	0.01	21.98	0
	70	4	24.43	13.89	0.00	-10.25	0.00	24.13	0	13.81	0.00	-10.41	0.01	24.22	0
	80	4	28.37	13.50	0.00	-14.40	0.00	27.89	0	13.58	0.00	-14.41	0.00	27.98	0
	90	4	31.61	12.92	0.00	-18.16	0.00	31.08	0	13.13	0.00	-18.12	0.00	31.25	0
	100	4	33.18	12.70	0.00	-19.95	0.00	32.65	0	12.77	0.00	-20.02	0.00	32.79	0
180	120	4	46.68	12.50	0.00	-33.69	0.00	46.19	0	12.35	0.00	-34.03	0.01	46.39	0
	140	2	40.36	11.93	0.00	-28.09	0.01	40.02	0	11.93	0.00	-28.10	0.00	40.04	0
	160	2	30.77	11.50	0.00	-18.77	0.00	30.27	0	11.51	0.00	-18.78	0.01	30.29	0
	180	2	27.56	11.16	0.00	-16.41	0.00	27.56	0	11.04	0.00	-16.55	0.00	27.60	0
	200	2	30.93	10.61	0.00	-20.35	0.00	30.96	0	10.66	0.00	-20.35	0.00	31.01	0
	250	1.5	38.90	9.61	0.00	-29.17	0.00	38.78	0	9.59	0.00	-29.35	0.01	38.94	0
400	300	1.5	45.51	8.64	0.00	-36.18	0.00	44.82	0	8.66	0.00	-36.36	0.01	45.01	0
	400	1.2	34.78	6.66	0.00	-27.97	0.00	34.63	0	6.62	0.00	-28.76	0.03	35.38	0
	500	2.3	40.89	4.71	0.00	-35.88	0.01	40.59	0	4.66	0.00	-35.59	0.00	40.24	0
700	600	2	42.07	2.73	0.00	-39.02	0.01	41.75	1	2.71	0.00	-38.78	0.01	41.49	0
	700	1.7	39.54	0.77	0.00	-38.71	0.00	39.48	0	0.80	0.00	-38.60	0.02	39.40	0
	800	1.5	41.96	-1.04	0.00	-43.70	0.02	42.65	0	-1.15	0.00	-43.23	0.02	42.08	0
	900	1.3	44.70	-2.65	0.00	-48.98	0.01	46.33	0	-2.73	0.00	-46.98	0.01	44.25	0
	1000	1.2	47.55	-4.07	0.00	-52.14	0.01	48.07	1	-4.14	0.00	-50.31	0.03	46.17	0

Table A.3: Measured SA at Locations 3 and 4

Dipole **[MHz]**	f [MHz]	h_r [m]	SA_c [dB]	U_{ra3} [dB]	σ_{Ura3}	U_{s3} [dB]	σ_{Us3}	SA_{m3} [dB]	Abs	U_{ra4} [dB]	σ_{Ura4}	U_{s4} [dB]	σ_{Us4}	SA_{m4} [dB]	Abs
60	30	4	55.10	15.47	0.00	-40.10	0.00	55.58	0	15.55	0.00	-40.13	0.00	55.68	0
	35	4	48.34	15.62	0.00	-32.29	0.00	47.92	0	15.45	0.00	-32.39	0.00	47.85	0
	40	4	41.97	14.53	0.00	-27.99	0.00	42.52	0	14.54	0.00	-28.10	0.00	42.64	0
	45	4	35.63	14.79	0.00	-20.78	0.00	35.57	0	14.91	0.00	-20.41	0.00	35.32	0
	50	4	29.33	14.27	0.00	-15.42	0.00	29.69	0	14.12	0.00	-15.60	0.00	29.73	0
	60	4	22.02	14.16	0.00	-7.84	0.01	22.01	0	14.05	0.00	-8.00	0.00	22.05	0
	70	4	24.43	13.97	0.00	-10.21	0.01	24.18	0	13.82	0.00	-10.41	0.00	24.24	0
	80	4	28.37	13.47	0.00	-14.35	0.00	27.82	0	13.61	0.00	-14.50	0.00	28.11	0
	90	4	31.61	13.02	0.00	-18.09	0.00	31.12	0	13.15	0.00	-18.10	0.00	31.25	0
	100	4	33.18	12.68	0.00	-19.97	0.00	32.65	0	12.79	0.00	-20.05	0.00	32.84	0
180	120	4	46.68	12.55	0.00	-33.69	0.00	46.24	0	12.36	0.00	-33.99	0.00	46.35	0
	140	2	40.36	11.92	0.00	-28.17	0.00	40.09	0	11.98	0.00	-28.09	0.00	40.08	0
	160	2	30.77	11.55	0.00	-18.87	0.00	30.42	0	11.53	0.00	-18.97	0.00	30.50	0
	180	2	27.56	11.19	0.00	-16.49	0.00	27.68	0	11.02	0.00	-16.63	0.00	27.65	0
	200	2	30.93	10.54	0.00	-20.27	0.00	30.81	0	10.70	0.00	-20.27	0.00	30.97	0
	250	1.5	38.90	9.59	0.00	-29.09	0.01	38.69	0	9.62	0.00	-29.41	0.00	39.03	0
400	300	1.5	45.51	8.67	0.00	-36.28	0.00	44.95	0	8.68	0.00	-36.50	0.01	45.18	0
	400	1.2	34.78	6.66	0.00	-27.99	0.01	34.65	0	6.60	0.00	-28.35	0.00	34.95	0
	500	2.3	40.89	4.60	0.00	-36.27	0.01	40.87	0	4.56	0.00	-36.06	0.00	40.62	0
700	600	2	42.07	2.67	0.00	-39.38	0.01	42.04	1	2.72	0.00	-39.83	0.00	42.54	3
	700	1.7	39.54	0.84	0.00	-38.19	0.01	39.03	1	0.77	0.00	-39.21	0.00	39.98	3
	800	1.5	41.96	-0.99	0.01	-43.37	0.00	42.38	3	-1.19	0.01	-43.11	0.01	41.92	3
	900	1.3	44.70	-2.67	0.00	-49.35	0.01	46.68	1	-2.74	0.01	-47.34	0.01	44.60	3
	1000	1.2	47.55	-4.21	0.00	-52.07	0.02	47.86	1	-4.07	0.01	-51.94	0.02	47.88	3

Table A.4: Measured SA at Locations 5 and 6

Dipole [**MHz**]	f [MHz]	h_r [m]	SA_c [dB]	U_{ra5} [dB]	σ_{Ura5}	U_{s5} [dB]	σ_{Us5}	SA_{m5} [dB]	Abs	U_{ra6} [dB]	σ_{Ura6}	U_{s6} [dB]	σ_{Us6}	SA_{m6} [dB]	Abs
60	30	4	55.10	15.57	0.00	-40.13	0.00	55.70	0	15.52	0.00	-40.17	0.00	55.69	0
	35	4	48.34	15.48	0.00	-32.36	0.00	47.83	0	15.43	0.00	-32.37	0.01	47.80	0
	40	4	41.97	14.59	0.00	-27.90	0.00	42.49	0	14.54	0.00	-28.05	0.00	42.59	0
	45	4	35.63	14.75	0.00	-20.77	0.00	35.53	0	14.85	0.00	-20.41	0.00	35.26	0
	50	4	29.33	14.07	0.00	-15.63	0.00	29.70	0	14.11	0.00	-15.60	0.00	29.71	0
	60	4	22.02	14.05	0.00	-7.96	0.01	22.01	0	14.07	0.00	-7.94	0.01	22.02	0
	70	4	24.43	13.83	0.00	-10.46	0.01	24.29	0	13.91	0.00	-10.29	0.01	24.20	0
	80	4	28.37	13.61	0.00	-14.50	0.00	28.10	0	13.64	0.00	-14.45	0.00	28.09	0
	90	4	31.61	13.15	0.00	-18.18	0.00	31.33	0	13.15	0.00	-18.03	0.00	31.19	0
	100	4	33.18	12.79	0.00	-20.10	0.00	32.90	0	12.78	0.00	-20.02	0.00	32.80	0
180	120	4	46.68	12.39	0.00	-34.04	0.00	46.42	0	12.32	0.00	-34.09	0.00	46.41	0
	140	2	40.36	11.97	0.00	-27.96	0.00	39.93	0	11.94	0.00	-28.07	0.00	40.01	0
	160	2	30.77	11.52	0.00	-18.80	0.00	30.32	0	11.48	0.00	-18.84	0.00	30.32	0
	180	2	27.56	11.08	0.00	-16.49	0.00	27.57	0	11.03	0.00	-16.55	0.00	27.57	0
	200	2	30.93	10.68	0.00	-20.31	0.00	30.99	0	10.64	0.00	-20.34	0.00	30.98	0
	250	1.5	38.90	9.60	0.00	-29.32	0.00	38.92	0	9.54	0.00	-29.22	0.00	38.76	0
400	300	1.5	45.51	8.68	0.00	-36.50	0.01	45.18	0	8.60	0.00	-36.23	0.02	44.83	0
	400	1.2	34.78	6.64	0.00	-28.33	0.00	34.98	0	6.55	0.00	-28.36	0.01	34.91	0
	500	2.3	40.89	4.60	0.00	-35.69	0.01	40.28	0	4.61	0.00	-36.26	0.01	40.87	0
700	600	2	42.07	2.63	0.00	-39.30	0.01	41.93	1	2.74	0.00	-38.28	0.01	41.02	0
	700	1.7	39.54	0.76	0.01	-38.46	0.01	39.22	1	0.80	0.00	-39.73	0.00	40.53	0
	800	1.5	41.96	-1.19	0.01	-42.84	0.03	41.65	1	-1.07	0.00	-42.46	0.01	41.39	0
	900	1.3	44.70	-2.78	0.00	-47.07	0.00	44.29	1	-2.69	0.00	-46.08	0.01	43.39	0
	1000	1.2	47.55	-4.17	0.00	-52.21	0.01	48.04	1	-4.04	0.00	-50.71	0.01	46.67	0

Table A.5: Measured SA at Locations 7 and 8

Dipole [**MHz**]	f [MHz]	h_r [m]	SA_c [dB]	U_{ra7} [dB]	σ_{Ura7}	U_{s7} [dB]	σ_{Us7}	SA_{m7} [dB]	Abs	U_{ra8} [dB]	σ_{Ura8}	U_{s8} [dB]	σ_{Us8}	SA_{m8} [dB]	Abs
60	30	4	55.10	15.40	0.00	-40.11	0.00	55.51	0	15.51	0.00	-40.19	0.00	55.70	0
	35	4	48.34	15.54	0.00	-32.31	0.00	47.85	0	15.44	0.00	-32.36	0.00	47.80	0
	40	4	41.97	14.47	0.00	-27.97	0.00	42.44	0	14.52	0.00	-28.12	0.00	42.64	0
	45	4	35.63	14.71	0.00	-20.84	0.00	35.55	0	14.89	0.00	-20.43	0.00	35.32	0
	50	4	29.33	14.21	0.00	-15.42	0.00	29.63	0	14.11	0.00	-15.68	0.00	29.80	0
	60	4	22.02	14.10	0.00	-7.85	0.00	21.96	0	14.05	0.00	-7.96	0.00	22.02	0
	70	4	24.43	13.90	0.00	-10.24	0.00	24.14	0	13.81	0.00	-10.34	0.01	24.15	0
	80	4	28.37	13.41	0.00	-14.41	0.00	27.81	0	13.61	0.00	-14.51	0.00	28.12	0
	90	4	31.61	12.97	0.00	-18.13	0.00	31.10	0	13.13	0.00	-18.02	0.00	31.16	0
	100	4	33.18	12.64	0.00	-20.04	0.00	32.67	0	12.78	0.00	-20.00	0.02	32.78	0
180	120	4	46.68	12.50	0.00	-33.77	0.00	46.27	0	12.33	0.00	-34.23	0.00	46.56	0
	140	2	40.36	11.87	0.00	-28.23	0.00	40.10	0	11.97	0.00	-27.93	0.00	39.90	0
	160	2	30.77	11.52	0.00	-18.81	0.00	30.33	0	11.50	0.00	-18.82	0.00	30.33	0
	180	2	27.56	11.13	0.00	-16.54	0.01	27.67	0	11.03	0.00	-16.21	0.00	27.24	0
	200	2	30.93	10.51	0.00	-20.09	0.01	30.59	0	10.66	0.00	-20.79	0.00	31.45	0
	250	1.5	38.90	9.56	0.00	-28.90	0.00	38.45	0	9.61	0.00	-29.83	0.00	39.44	0
400	300	1.5	45.51	8.64	0.00	-36.11	0.00	44.74	0	8.67	0.00	-36.55	0.00	45.21	0
	400	1.2	34.78	6.66	0.00	-27.95	0.00	34.60	0	6.59	0.00	-28.38	0.00	34.96	0
	500	2.3	40.89	4.60	0.00	-35.72	0.01	40.31	0	4.57	0.00	-35.86	0.00	40.43	0
700	600	2	42.07	2.71	0.00	-39.18	0.01	41.89	0	2.70	0.00	-39.33	0.01	42.03	1
	700	1.7	39.54	0.78	0.01	-39.26	0.01	40.04	1	0.73	0.00	-38.18	0.01	38.91	1
	800	1.5	41.96	-0.98	0.00	-43.39	0.03	42.41	1	-1.21	0.00	-43.56	0.01	42.35	1
	900	1.3	44.70	-2.69	0.01	-47.09	0.11	44.41	0	-2.72	0.00	-47.19	0.00	44.47	1
	1000	1.2	47.55	-4.08	0.01	-52.19	0.01	48.10	1	-4.06	0.00	-50.71	0.01	46.65	1

Table A.6: Measured SA at Location 9

Dipole **[MHz]**	f [MHz]	h_r [m]	SA_c [dB]	U_{ra9} [dB]	σ_{Ura9}	U_{s9} [dB]	σ_{Us9}	SA_{m9} [dB]	Abs
60	30	4	55.10	15.39	0.00	-40.29	0.00	55.68	0
	35	4	48.34	15.58	0.00	-32.35	0.00	47.94	0
	40	4	41.97	14.51	0.00	-28.10	0.00	42.61	0
	45	4	35.63	14.90	0.00	-20.53	0.00	35.42	0
	50	4	29.33	14.24	0.00	-15.59	0.00	29.83	0
	60	4	22.02	14.20	0.00	-7.86	0.00	22.05	0
	70	4	24.43	13.91	0.00	-10.23	0.01	24.15	0
	80	4	28.37	13.52	0.00	-14.50	0.00	28.02	0
	90	4	31.61	12.95	0.00	-18.16	0.00	31.11	0
	100	4	33.18	12.73	0.00	-20.01	0.00	32.74	0
180	120	4	46.68	12.54	0.00	-33.74	0.00	46.28	0
	140	2	40.36	11.98	0.00	-27.84	0.00	39.82	0
	160	2	30.77	11.53	0.00	-18.97	0.00	30.50	0
	180	2	27.56	11.16	0.00	-16.55	0.01	27.70	0
	200	2	30.93	10.66	0.00	-20.32	0.01	30.98	0
	250	1.5	38.90	9.66	0.00	-29.11	0.00	38.78	0
400	300	1.5	45.51	8.68	0.00	-36.14	0.00	44.82	0
	400	1.2	34.78	6.68	0.00	-28.36	0.00	35.04	0
	500	2.3	40.89	4.73	0.00	-35.85	0.01	40.58	0
700	600	2	42.07	2.70	0.00	-39.12	0.01	41.83	1
	700	1.7	39.54	0.82	0.00	-39.06	0.01	39.89	1
	800	1.5	41.96	-1.03	0.01	-43.32	0.02	42.28	1
	900	1.3	44.70	-2.66	0.00	-46.87	0.01	44.21	1
	1000	1.2	47.55	-4.08	0.00	-53.89	0.02	49.81	1

Table A.7: Theoretical Receiver Antenna Height Values at 300 MHz

h_t [m]	h_r [m]	SA_c 300 MHz [dB]	h_r [m]	SA_c 300 MHz [dB]	h_r [m]	SA_c 300 MHz [dB]	h_r [m]	SA_c 300 MHz [dB]
2	1.00	32.58	1.30	32.36	1.60	32.5	1.90	34.99
2	1.01	32.49	1.31	32.39	1.61	32.54	1.91	35.07
2	1.02	32.40	1.32	32.42	1.62	32.59	1.92	35.15
2	1.03	32.31	1.33	32.44	1.63	32.64	1.93	35.23
2	1.04	32.23	1.34	32.47	1.64	32.69	1.94	35.30
2	1.05	32.16	1.35	32.48	1.65	32.75	1.95	35.38
2	1.06	32.09	1.36	32.50	1.66	32.82	1.96	35.46
2	1.07	32.03	1.37	32.51	1.67	32.90	1.97	35.54
2	1.08	31.98	1.38	32.51	1.68	32.97	1.98	35.62
2	1.09	31.94	1.39	32.52	1.69	33.06	1.99	35.71
2	1.10	31.90	1.40	32.52	1.70	33.14	2.00	35.79
2	1.11	31.87	1.41	32.51	1.71	33.23	2.01	35.88
2	1.12	31.86	1.42	32.51	1.72	33.32	2.02	35.97
2	1.13	31.85	1.43	32.50	1.73	33.42	2.03	36.07
2	1.14	31.84	1.44	32.49	1.74	33.51	2.04	36.17
2	1.15	31.85	1.45	32.48	1.75	33.61	2.05	36.28
2	1.16	31.86	1.46	32.47	1.76	33.71	2.06	36.39
2	1.17	31.88	1.47	32.45	1.77	33.81	2.07	36.51
2	1.18	31.90	1.48	32.44	1.78	33.91	2.08	36.63
2	1.19	31.93	1.49	32.43	1.79	34.00	2.09	36.76
2	1.20	31.97	1.50	32.42	1.80	34.10	2.1	36.90
2	1.21	32.00	1.51	32.41	1.81	34.20	2.11	37.04
2	1.22	32.04	1.52	32.40	1.82	34.29	2.12	37.19
2	1.23	32.08	1.53	32.40	1.83	34.38	2.13	37.35
2	1.24	32.13	1.54	32.40	1.84	34.48	2.14	37.52
2	1.25	32.17	1.55	32.40	1.85	34.56	2.15	37.69
2	1.26	32.21	1.56	32.41	1.86	34.65	2.16	37.87
2	1.27	32.25	1.57	32.43	1.87	34.74	2.17	38.06
2	1.28	32.29	1.58	32.45	1.88	34.82	2.18	38.25
2	1.29	32.33	1.59	32.47	1.89	34.91	2.19	38.46

Table A.8: Theoretical Receiver Antenna Height Values at 300 MHz, cont.

h_t [m]	h_r [m]	SA_c 300 MHz [dB]	h_r [m]	SA_c 300 MHz [dB]	h_r [m]	SA_c 300 MHz [dB]
2	2.20	38.66	2.50	48.65	2.80	46.60
2	2.21	38.88	2.51	49.26	2.81	46.16
2	2.22	39.10	2.52	49.91	2.82	45.74
2	2.23	39.33	2.53	50.61	2.83	45.34
2	2.24	39.56	2.54	51.36	2.84	44.96
2	2.25	39.80	2.55	52.17	2.85	44.59
2	2.26	40.05	2.56	53.05	2.86	44.24
2	2.27	40.30	2.57	53.98	2.87	43.90
2	2.28	40.55	2.58	54.97	2.88	43.57
2	2.29	40.82	2.59	55.99	2.89	43.25
2	2.30	41.08	2.6	56.98	2.90	42.94
2	2.31	41.36	2.61	57.84	2.91	42.64
2	2.32	41.64	2.62	58.43	2.92	42.35
2	2.33	41.92	2.63	58.60	2.93	42.06
2	2.34	42.22	2.64	58.30	2.94	41.79
2	2.35	42.52	2.65	57.62	2.95	41.52
2	2.36	42.83	2.66	56.71	2.96	41.26
2	2.37	43.14	2.67	55.72	2.97	41.00
2	2.38	43.47	2.68	54.72	2.98	40.75
2	2.39	43.81	2.69	53.76	2.99	40.51
2	2.40	44.15	2.70	52.86	3.00	40.28
2	2.41	44.51	2.71	52.01		
2	2.42	44.89	2.72	51.23		
2	2.43	45.28	2.73	50.51		
2	2.44	45.69	2.74	49.83		
2	2.45	46.12	2.75	49.21		
2	2.46	46.57	2.76	48.62		
2	2.47	47.04	2.77	48.07		
2	2.48	47.55	2.78	47.55		
2	2.49	48.080	2.79	47.06		

Table A.9: Theoretical Receiver Antenna Height Values at 600 MHz

h_t [m]	h_r [m]	SA_c 600 MHz [dB]	h_r [m]	SA_c 600 MHz [dB]	h_r [m]	SA_c 600 MHz [dB]	h_r [m]	SA_c 600 MHz [dB]
2	1.00	42.03	1.30	64.63	1.60	41.34	1.90	38.33
2	1.01	42.23	1.31	61.30	1.61	41.17	1.91	38.34
2	1.02	42.46	1.32	58.79	1.62	41.00	1.92	38.34
2	1.03	42.71	1.33	56.84	1.63	40.85	1.93	38.33
2	1.04	42.99	1.34	55.25	1.64	40.70	1.94	38.33
2	1.05	43.30	1.35	53.92	1.65	40.55	1.95	38.32
2	1.06	43.64	1.36	52.78	1.66	40.41	1.96	38.31
2	1.07	44.01	1.37	51.79	1.67	40.26	1.97	38.30
2	1.08	44.42	1.38	50.91	1.68	40.12	1.98	38.29
2	1.09	44.86	1.39	50.12	1.69	39.97	1.99	38.28
2	1.10	45.34	1.40	49.40	1.70	39.82	2.00	38.28
2	1.11	45.85	1.41	48.74	1.71	39.68		
2	1.12	46.39	1.42	48.12	1.72	39.53		
2	1.13	46.96	1.43	47.54	1.73	39.38		
2	1.14	47.57	1.44	46.99	1.74	39.24		
2	1.15	48.21	1.45	46.47	1.75	39.10		
2	1.16	48.89	1.46	45.98	1.76	38.97		
2	1.17	49.62	1.47	45.50	1.77	38.85		
2	1.18	50.41	1.48	45.05	1.78	38.74		
2	1.19	51.26	1.49	44.62	1.79	38.65		
2	1.20	52.20	1.50	44.21	1.80	38.56		
2	1.21	53.25	1.51	43.82	1.81	38.49		
2	1.22	54.44	1.52	43.45	1.82	38.44		
2	1.23	55.84	1.53	43.10	1.83	38.40		
2	1.24	57.50	1.54	42.78	1.84	38.37		
2	1.25	59.56	1.55	42.49	1.85	38.35		
2	1.26	62.23	1.56	42.22	1.86	38.33		
2	1.27	65.80	1.57	41.97	1.87	38.33		
2	1.28	69.75	1.58	41.74	1.88	38.33		
2	1.29	68.78	1.59	41.53	1.89	38.33		

Table A.10: Theoretical Receiver Antenna Height Values at 900 MHz

h_t [m]	h_r [m]	SA_c 900 MHz [dB]	h_r [m]	SA_c 900 MHz [dB]	h_r [m]	SA_c 900 MHz [dB]	h_r [m]	SA_c 900 MHz [dB]
2	1.00	47.37	1.30	41.77	1.60	49.25	1.90	46.25
2	1.01	46.81	1.31	41.77	1.61	49.97	1.91	45.87
2	1.02	46.29	1.32	41.76	1.62	50.75	1.92	45.53
2	1.03	45.83	1.33	41.77	1.63	51.61	1.93	45.21
2	1.04	45.42	1.34	41.78	1.64	52.55	1.94	44.91
2	1.05	45.06	1.35	41.82	1.65	53.62	1.95	44.62
2	1.06	44.75	1.36	41.87	1.66	54.85	1.96	44.34
2	1.07	44.48	1.37	41.96	1.67	56.29	1.97	44.07
2	1.08	44.24	1.38	42.07	1.68	58.04	1.98	43.81
2	1.09	44.01	1.39	42.21	1.69	60.24	1.99	43.56
2	1.10	43.80	1.40	42.38	1.70	63.16	2.00	43.32
2	1.11	43.60	1.41	42.57	1.71	67.17		
2	1.12	43.39	1.42	42.77	1.72	71.29		
2	1.13	43.18	1.43	42.98	1.73	68.83		
2	1.14	42.97	1.44	43.20	1.74	64.46		
2	1.15	42.76	1.45	43.42	1.75	61.25		
2	1.16	42.55	1.46	43.65	1.76	58.86		
2	1.17	42.36	1.47	43.87	1.77	56.97		
2	1.18	42.18	1.48	44.10	1.78	55.43		
2	1.19	42.03	1.49	44.35	1.79	54.11		
2	1.20	41.90	1.50	44.60	1.80	52.96		
2	1.21	41.81	1.51	44.89	1.81	51.95		
2	1.22	41.75	1.52	45.20	1.82	51.04		
2	1.23	41.72	1.53	45.54	1.83	50.21		
2	1.24	41.70	1.54	45.93	1.84	49.46		
2	1.25	41.71	1.55	46.37	1.85	48.78		
2	1.26	41.72	1.56	46.85	1.86	48.16		
2	1.27	41.74	1.57	47.38	1.87	47.61		
2	1.28	41.75	1.58	47.96	1.88	47.11		
2	1.29	41.76	1.59	48.58	1.89	46.65		

Table A.11: Temperature and Relative Humidity at the Tested Dates

Date	**Min Temp** [°C]	**Max Temp** [°C]	**Min Hum** [%]	**Max Hum** [%]
13 Nov 12	21.7 ± 0.3	29.5 ± 0.3	35.0 ± 0.8	49.5 ± 0.9
16 Nov 12	33.2 ± 0.3	42.5 ± 0.3	18.1 ± 0.6	47.6 ± 0.9
20 Nov 12	35.7 ± 0.3	42.5± 0.3	11.6 ± 0.6	33.1 ± 0.7
21 Nov 12	22.5± 0.3	39.1 ± 0.3	25.2 ± 0.7	49.5 ± 0.9
22 Nov 12	18.1 ± 0.3	38.0 ± 0.3	10.9 ± 0.6	57.0 ± 1.1
26 Nov 12	23.3 ± 0.3	33.6 ± 0.3	28.7 ± 0.7	31.5 ± 0.7
3 Dec 12	22.6 ± 0.3	42.5 ± 0.3	7.6 ± 0.6	33.8 ± 0.7
10 Dec 12	19.8 ± 0.3	29.7 ± 0.3	20.2 ± 0.6	43.7 ± 0.9
13 Dec 12	13.7 ± 0.3	27.1 ± 0.3	29.2 ± 0.7	78.1 ± 1.4
18 Dec 12	18.4 ± 0.3	39.6 ± 0.3	13.5 ± 0.6	60.6 ± 1.1
19 Dec 12	21.0 ± 0.3	42.5 ± 0.3	22.4 ± 0.6	43.1 ± 0.9
7 Jan 13	17.3 ± 0.3	35.0 ± 0.3	18.3 ± 0.6	55.8 ± 1.0
8 Jan 13	18.7 ± 0.3	28.4 ± 0.3	32.0 ± 0.7	54.1 ± 1.0
9 Jan 13	22.8 ± 0.3	33.9 ± 0.3	22.6 ± 0.6	42.7 ± 0.9
14 Feb 13	33.5 ± 0.3	42.5 ± 0.3	-1.6 ± 0.6	7.5 ± 0.6
18 Feb 13	37.9 ± 0.3	42.5 ± 0.3	2.2 ± 0.6	6.8 ± 0.6
19 Feb 13	22.4 ± 0.3	34.7 ± 0.3	1.3 ± 0.6	8.0 ± 0.6