Antenna Time-Domain Measurement Techniques

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1. Abstract

The results of an experimental study, in which time-domain pulses are used to measure the far-field characteristics of an antenna, are presented. Pulses with duration and rise time of the order of 50 ps are generated, in order to characterize the complete frequency (1-18 GHz) behavior of an antenna. An X-band standard-gain horn has been used to verify the overall performance of the measurement system. Excellent agreement between the time-domain and the frequency-domain measurements has been observed. This paper describes the Antenna Time-Domain Measurement (ATDM) technique, time-domain gating, the error sources, and the advantages and the disadvantages of such a measurement technique.

2. Introduction

The increasingly demanding performance required of today's antennas necessitates higher-accuracy measurement techniques. Much attention has been given to far- and near-field antenna measurements in the frequency domain. Recently, the Antenna Time-Domain Measurement (ATDM) technique has received considerable attention [1, 2]. The work described herein is motivated by the fact that the measurement times associated with conventional frequency-domain techniques can be excessively long for electrically large and or sophisticated antennas, phased-array antennas, and multi-beam antennas in radar. Such antenna systems have to be tested over the whole frequency band. A dramatic reduction in the duration of measurements for antennas and scatterers can be achieved by using the ATDM technique. Time-domain gating, to filter the multiple reflections, gives a substantial improvement in measurement accuracy. A novel implementation of the ATDM incorporates a pulse generator, a sampling oscilloscope, and a sampling unit. This equipment is used to excite the antenna under test (AUT) with a short-time pulse, and to register the probe output signal. This paper presents an introduction to the method, and discusses the unique hardware implementation at IRCTR.

3. Advantages and disadvantages of ATDM

ATDM offers some advantages over the classical antenna-measurement technique in the frequency domain. These are as follows.

Direct gating. The reflections caused by mismatching and unwanted multiple reflections in an antenna range can be removed, using time-domain gating. The time gating in ATDM is applied directly to the measured signal (Figure 1).

Reduction of measurement time. Dramatic reduction factors can be achieved in the case of wideband antennas. The frequency response can be measured in only one session of measurement.

Removal of scan-plane errors in near-field measurements. In planar near-field measurements, a scan plane with finite size is used. This results in a scan-plane error. In [3, 4, 5], Hansen and Yaghjian have shown that the scan-plane error can be removed by using time gating.

Simple measurement set-up. ATDM equipment is less complex than comparable frequency-domain equipment, and therefore commercially attractive.

Antenna diagnosis. Reflections caused by mismatching in the antenna network can be easily observed from the measured time response.

The main disadvantages of the ATDM method are the following.

Reduction in S/N. The spectrum of the measurement pulse decays with frequency. The resulting reduction of S/N (signal-to-noise) ratio results in a low measurement accuracy at higher frequencies.

Figure 1. The effect of reflections in ATDM.

Narrow-band antennas. ATDM is less preferable for antennas with non-wideband characteristics.

4. Time-domain pulses

The AUT is excited with short-duration time pulses. Two important aspects of these pulse signals are the pulse spectrum and the pulse energy. The pulse spectrum determines the distribution of the energy of the time signal over each individual spectral component. The S/N ratio of spectral components is directly proportional to the energy of each component. The larger the signal-to-noise ratio, the more accurate are the measurements. The pulse energy, E_p , and the pulse spectrum, $P(f)$, are related to the pulse signal by the following equations [$p(t)$ is the pulse amplitude as a function of time]:

$$E_p \equiv \int_{-\infty}^{\infty} |p(t)|^2 dt, \quad (1)$$

$$P(f) = \int_{-\infty}^{\infty} p(t) e^{-j2\pi ft} dt. \quad (2)$$

For short time pulses, the pulse energy is distributed over a large number of frequency components. In order to obtain sufficient energy per spectral component, the amplitude of the pulse should be increased.

5. Error sources in ATDM

The error sources in the time-domain measurements can be divided into two groups: the short-term and long-term error sources.

5.1 Short-term error sources

These fast variations are uncorrelated from one measurement to another. Three types of short-term error sources can be distinguished in ATDM: thermal noise, jitter, and quantization noise. Only jitter is discussed here, because this error source is specific for ATDM. Jitter is the non-deterministic variation in sample position. Figure 2 shows the voltage error resulting from a variation in sample position.

If the signal slope is locally constant, then the voltage error distribution is equal to the jitter distribution times the slope. The time error distribution is considered to be Gaussian. If the slope is not constant, then the analysis of the errors caused by the jitter is more complicated [6, 7].

5.2 Long-term error sources

Long-term variations are due to changes in the position and shape of the measurement pulse. These long term variations are mainly caused by effects of the measurement environment and imperfections in the system.

The variations in the pulse shape result in amplitude variations. The variations in the pulse position ("drift") result in phase errors. The magnitude of the phase error can be derived using

Fourier theory. Assuming a drift of Δt , the phase deviation, $\Delta\phi$, is given by

$$\Delta\phi = 2\pi f_c \Delta t. \quad (3)$$

The time-domain equipment used in DUCAT (Delft University Chamber for Antenna Tests) shows a drift of 10 ps over three hours. This drift causes a phase deviation of 36° at 10 GHz. For the Delft ATDM equipment, drift is the most dominant long-term error source. Long-term variations can be corrected using a reference signal.

6. Practical measurement setup

In the IRCTR laboratory, there is a moderately sized anechoic chamber called DUCAT (Delft University Chamber for Antenna Tests). DUCAT has, over the years, been successfully used to measure far-field antenna patterns for electrically small antennas, near-field measurements for electrically large antennas, and for RCS measurements. The standard measurement equipment within DUCAT consists of an HP 8510B network analyzer, an HP 8341 B synthesized sweeper (RF source), and an HP 8350/HP 83592 B sweep oscillator (LO source). This equipment is controlled by an HP 9000/320 computer. The time-domain measurement system, K2-63, has been developed and integrated in DUCAT in a cooperative project between the RTI (Radio Technical Institute) in Moscow, and the IRCTR. The DUCAT-ATDM system consists of the following equipment.

K2-63-1 sampling oscilloscope. This instrument controls the sampling unit and the pulse generator with trigger pulses. The received waveforms in the sampling unit are transferred to the sampling oscilloscope via a data cable. The sampling oscilloscope processes the data and displays it. In total, four channels can be measured simultaneously. The sampling oscilloscope can be operated manually or with a computer through the GPIB interface (IEEE 488.1 standard).

K2-63-2 pulse generator. This instrument can generate three different pulses: the step pulse, the block pulse, and the delta pulse. The step pulse has a rise time of 60 ps, and an amplitude that can

Figure 2. The description of jitter in time-domain measurements.

be controlled between 15 V and 30 V. Rise time is defined as the time in which the amplitude rises from 10% to 90% of the maximum value. The block pulse has a 50% pulse width of 190 ps, and an amplitude of 40 V. The delta pulse can be generated using a pulse shaper. The output of the shaper is a delta pulse with a 50% width of 85 ps, and an amplitude of 30 V. A second pulse shaper can be used, in combination with the block pulse, to generate a pulse with a 50% width of 30 ps, and an amplitude of 5V.

K2-63-3 sampling unit. This instrument samples the received waveform. The sampling unit has four channels: two channels with a bandwidth of 1-6 GHz, and another two channels with a bandwidth of 1-18 GHz.

Reference channel. The reference channel is included to compensate for the long-term effects in the pulse position and shape.

Pentium PC. The PC controls the measurement equipment and allows for automated measurement.

Tables 1 and 2 show the characteristics of the sampling oscilloscope and the pulse generator.

Table 1: The characteristics of the sampling oscilloscope.

Parameter	Value
Number of channels	4
Bandwidth	2 × (1-6 GHz) 2 × (1-18 GHz)
Noise (RMS)	≤ 1.0 mV (1-6 GHz) ≤ 4.0 mV (1-18 GHz)
Max. input voltage	± 1.0 V
Voltage measurement accuracy	±(0.02 V_x + 0.002) V
A/D converter	12 bits
Number of samples	256, 512, 1024, 2048
Max. averaging	256
Minimum sampling time	0.1 ps
Jitter	≤ 2.0 ps
Measurement range	10.0 ps - 10 μ s

Table 2: The characteristics of the pulse generator.

Parameter	Value
Type 1 ("step pulse")	
Amplitude (controllable)	15-30 V
10%-90% rise time	60 ps
Type 2 ("block pulse")	
Amplitude	40 V
50% pulse width	190 ps
Type 3 ("delta pulse"+shaper 1)	
Amplitude	30 V
50% pulse width	85 ps
Type 4 ("block pulse"+shaper 2)	
Amplitude	-5 V
50% pulse width	30 ps
Pulse repetition rate	10 - 100 kHz

Figure 3. The time signal delta pulse with shaper 1.

Figure 4. The S/N measurement setup.

Figure 5. The S/N ratio delta pulse with shaper 1.

Figure 6. The standard deviation in phase for the delta pulse with shaper 1.

Figure 7. The ATDM setup in DUCAT.

Figure 8. The time response of the X-band standard-gain horn on the main axis.

Figure 9. The S/N ratio for the specified frequency range of the standard-gain horn.

7. Measurement results

Several experiments were performed to check out the overall characteristics of the ATDM equipment. The optimum S/N ratio and phase error of the system were measured. These parameters play an essential role in the overall accuracy of the ATDM. Figure 3 shows the measured time-domain response of the delta pulse, using shaper 1.

For this pulse, the S/N ratio of the system and the standard deviation of the phase error are measured. Figure 4 shows the

measurement setup for measuring the S/N ratio. The output of the pulse shaper is connected via an 1 m RF cable and two 20 dB attenuators to the sampling unit. Two attenuators are used in order to limit the maximum input signal to the sampling unit to 300 mV. The output signal is sampled with a sampling time of 2.0 ps, and each sample is averaged over 256 observations. A total of 1024 samples are taken for DFT transformation. The DC offset of the pulse is compensated, and a raised-cosine windowing function is used. Figures 5 and 6 show the measured S/N ratio and standard deviation of the phase error. The measured S/N ratio is compared to the frequency spectrum of the time signal in Figure 5. Note that S/N decreases as a function of frequency, and follows very well the spectral-density function.

The S/N ratio and phase error, shown in Figures 5 and 6, are corrected for the two attenuators used.

The pulse, shown in Figure 3, is used to measure the characteristics of the X-band standard-gain horn for the main axis and the radiation pattern. Figure 7 shows the ATDM setup in the DUCAT. Two linearly polarized standard-gain horns in the X-band were used for the AUT and the probe.

Figure 8 shows the main-axis response of the standard-gain horn. A time window of 4 ns was chosen.

Figure 9 shows the S/N ratio as a function of frequency for the standard-gain horn. Figure 9 gives an indication of the measurement accuracy for the standard-gain horn at X-band. The output signal is sampled, with a sampling time of 4.0 ps, and each sample

Figure 10. A comparison of the far-field pattern for a time and a frequency-domain measurement at 11.23 GHz: E plane.

Figure 11. A comparison of the far-field pattern for a time and a frequency-domain measurement at 11.23 GHz: H plane.

is averaged over 256 observations. A total of 1024 samples are taken for DFT transformation. A raised-cosine windowing function is used.

Figures 10 and 11 are comparison patterns of the standard-gain horn at 11.23 GHz, in the *E*-plane and the *H*-plane, respectively. These far-field patterns are obtained using the DUCAT frequency and time-domain equipment. Excellent agreement is noted between the frequency and time-domain measurements.

8. Conclusions

A novel, customized, antenna time-domain measurement technique has been presented as an alternative to the classical frequency-domain techniques. This configuration is practical, accurate, uses less equipment, requires less time for measurement over a wide frequency band, and is capable of measuring the antenna patterns in the far and near fields. This paper is an introduction to the ATDM far-field measurement concept, including the unique hardware implementation at IRCTR and, what is most important, it shows measured results.

A standard-gain horn at X-band was used to check the overall performance of the system. Direct comparison with a traditional frequency-domain measurement yielded excellent agreement for each frequency component. In the future, the near-field time-domain measurement technique will be implemented.

9. References

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Introducing Feature Article Authors

Rene V. de Jongh was born on January 16, 1971. In 1994, he received the MS degree in Electrical Engineering from Delft University of Technology. In 1996, he completed a post-graduate designer course at Delft University of Technology, and was registered as a "Chartered Designer" at the Royal Dutch Association of Engineers (KIVI). The designer course comprised the implementation and verification of time-domain antenna measurements.

Mr. de Jongh's professional interests include the areas of radar systems, especially ground-penetrating-radar (GPR) systems, and the application of the time-domain method in antenna measurements. He is involved in the development of improved antenna systems for ground-penetrating radar, development of new concepts for using GPR in land-mine detection, and the implementation of the time-domain method in near-field antenna measurements.

Mostafa Hajian was born in Iran, on April 21, 1957. He received the BS degree in physics from the University of Oklahoma, in 1980, and the MS in Electrical Engineering from Delft University of Technology, in 1990. Since 1991, he has been working at Delft University, where he teaches graduate courses in antennas. His research interests are antenna-measurement techniques, imaging, and millimeter-wave antennas.

Leo P. Ligthart was born on September 15, 1946. He received his MS degree in Electrical Engineering from the Delft University of Technology, in 1969. After his MS degree, he started

working for Delft University of Technology. He received his PhD in 1985, from Delft University of Technology. He was a Professor in the Electronic Systems for Positioning and Navigation (radar) from 1988 to 1991. Since 1992, he has been a Professor in Microwave Transmission, Radar, and Remote Sensing. In 1994, he became the first Director of the International Research Centre for Telecommunications-transmission and Radar (IRCTR). The research institute IRCTR (part of the Delft University) concentrates on international cooperation in scientifically challenging projects in the fields of antennas, remote sensing, radar, and mobile communications.

Dr. Ligthart is a Fellow of the Institute of Electrical Engineers (IEE), and a member of NNC/URSI, COST, and NERG (Netherlands Electronics and Radio Society). His current research activities are in the fields of radio propagation, multi-function antennas, radar remote sensing, multi-parameter radar, radar networking, and microwave transmission. ☺

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Editor's Comments *Continued from page 6*

ence is not "strictly" antennas and propagation, and yet it is in a field that is of tremendous economic and technical importance, and uses our technology. Those who want more details about particular presentations can order the proceedings. If you're involved in organizing a conference that would be of interest to our readers, please consider planning such a report as an integral part of your conference. If you'll simply ask each session chair to write a paragraph highlighting the most significant material presented in his or her session, you'll have most of the report done by the end of the conference! If you attend a conference of interest and find that a report isn't planned (or even if it is!), please consider sharing your experiences with us.

G.G. Gentili, G. Pelosi, and R. Ravanelli have developed software to aid in the design of corrugated feed horns, and it is available from them. See John Volakis' EM Programmer's Notebook for details. If you are aware that *Java* may be something other than a bitter-tasting, dark beverage usually served hot (hmm...can you tell that I'm not a coffee drinker?), you should read Dennis Swift's Threads.

There are several important calls for papers in this issue. In particular, please note the MMET'98 1998 International Conference on Mathematical Methods in Electromagnetic Theory, to be held June 2-5, 1998, in Kharkov, Ukraine. This call should have appeared in a previous issue, but there is still time to submit a paper. Also, the 1998 IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting deadline is fast approaching. Our annual Symposium will be in Atlanta, Georgia, June 21-26, 1998. There are many innovations being added for this meeting, and it definitely is one not to miss. The deadline for submitting a paper is either January 5 or January 12, depending on how you submit it (electronic submission is the preferred option, but you *must* read the call for papers and other information before using it!).

A new addition to the Staff. Randy Haupt joins the *Magazine* Staff in this issue with a column devoted to professional ethics. This is an interesting topic, and one that I think is very important to our profession. Read his first column, and then send him your ideas. These can be ethical problems you have faced, or seen occur. They can be topics you would like to see discussed in his

column. They can also be comments on what appears in his column. Part of what will make this an interesting addition is the reader involvement it will hopefully generate, so participate!

We have a backlog—but it isn't a problem! In the more than 13 years that I have been editing this publication and its predecessor, we have rarely had more than about two issue's worth of feature articles "in hand." Currently, we have about a year's worth of feature articles either accepted for publication, or under review. That is really wonderful, and our readers and I appreciate what it says about our authors' support of the *Magazine*. However, this is not our normal situation. People submitting articles to the *Magazine* have come to expect that their submissions, if accepted, will probably appear within about six months or less. It is also a rather recent phenomenon: the rate of submissions started increasing at the end of last year, and has remained higher through the first half of this year and well into the summer. It has dropped off slightly in the last two months, and I really hope that is an aberration: I love this situation! It's still somewhat too soon to tell if the higher rate of submissions is going to continue. I've talked with some of our Officers and some AdCom members, and we're going to try to publish more feature articles in each issue for a few issues. This will lower the publication time, and it will also bring you, our readers, more interesting material in each issue. One effect of all of this is that it has put a bit of a strain on our reviewing system and our reviewers. Thus, the time from first submission to results of the review process has actually gone as long as six months in two or three cases, recently. Although that is much better than almost all other IEEE publications, I think that's too long, and we're taking steps to shorten it. The average is probably around three months right now, and given our current rate of submissions, that does not seem too unreasonable. If your recently submitted article has taken longer to be reviewed than it would have in previous years, please understand the situation.

The issue of whether to publish more features per issue, or to let the publication times stretch out, is not a simple one. In the best of all worlds, we would publish as many features per issue as we could, and still maintain quality and have sufficient articles for each issue. We can't do that to the extent we might like: it puts too much strain on our all-volunteer Staff, and it may cost too much. Even the economics are not simple. Each page we publish costs a certain amount, both to produce and print, as well as to mail (the current annual postage cost to mail a year's worth of *Magazine* issues to an AP-S member in the US is more than the \$12 AP-S membership fee; the postage cost for members on other continents is three to four times higher.) Adding pages increases the total cost. However, it also can increase our revenue: if we include them in our page budget, and if we set our non-member subscription price at the right level, additional pages mean a larger part of the IEEE All Publications Package revenue for the *Magazine*. Even that is very complicated. We essentially have to predict our page budget almost two years in advance (and we certainly didn't predict this increase in submissions). If we increase the number of pages we publish now (as opposed to, say, a year from now, when we have included it in our page budget), we will probably produce a net increase in cost, rather than revenue. The feeling among those with whom I've spoken is that even if it does cost us more, it is a good use of AP-S money. Obviously, this is an issue the AdCom will need to consider at the January meeting. I simply wanted you to know what was happening, and why some of the "time scales" of our *Magazine* have changed. If you have comments or suggestions, please let me know.

Continued on page 20