Comparisons of Pattern Measurements from Two Near-Field Systems
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Abstract
Antenna patterns are perhaps the most difficult parameter to measure accurately. The measurement accuracy is often contentious, including basic repeatability. The power gain, or else the co-polarized power gain, in the expected maximum direction is usually the focus of an accuracy specification, following a tradition of point-to-point free-space links. It follows that for a specification of measurement accuracy, many antennas or systems are characterized by maximum gain only. For accurate link budgets, the in-situ total gain is the most important, but time-varying scatterers in or near the Fresnel zone, - and for long-distance links, varying refraction - can introduce time-variations in a direct measurement. The estimation accuracy of a direct measurement is at its best for maximum gain because this has the maximum SNR. But complete patterns are also important, and the preferred measurement approach is via the near-fields, despite the pattern parameters, such as maximum directivity, being estimated indirectly. Various correlations of the patterns can provide useful information about the complete patterns (or selected portions of them), including an indication of measurement repeatability. This paper presents gains and pattern correlations of pattern measurements from two professional-grade systems which have similar, but not identical, configurations. The results provide a feel for the pattern repeatability from using compatible professional-grade measurement systems, and real-world factors including different operators and procedures. The testing antenna is a simple low-gain dual patch antenna.

1 Background and Introduction
Far-field patterns are a critical parameter of antennas, but they are very difficult to measure, requiring specialized equipment. They are fundamental to the analysis of communications and sensing systems. The gain, directivity and radiation efficiency (ratio of gain-to-directivity) are often used for antenna performance specification.

The required accuracy of the pattern depends on the antenna type and application. For example, [1] suggests that high-gain satellite antennas require gain measurements with an extreme accuracy of ±0.2dB, while lower gain antennas often require a peak gain measurement accuracy of about ±0.7dB. An accuracy of ±0.2dB requires traceable gain standards because the usual specified gain accuracy of a standard gain antenna is often ±0.5dB.

Far-field measurements offer the comfort of a direct measurement of the pattern, i.e., the complex gain in a given direction. But the drawbacks are considerable: far-field ranges need to be large (several kilometers for highly directive antennas at high frequencies), they are subject to RF interference and scattering including a ground reflection, they require high levels of power for a good signal-to-noise ratio (SNR) for all the directions, and they are also subject to having test equipment being exposed to an outdoor situation. Because of these drawbacks, near-field measurements have become the preferred approach, despite that the measured parameter must be found indirectly - the near-fields are probed in both polarizations over an enclosing surface (or enough of an enclosing surface to capture nearly all the power) and these are mathematically transformed to the far-field pattern, from which the directivity and other pattern parameters are derived. The way is open therefore for errors not just from thousands of individual near-field probe measurements, but also from the accuracy of the robotics for the probing, and the ensuing signal processing. But the use of an anechoic chamber for the near-field measurement allows an electromagnetically screened environment with suppressed interference to and from other spectrum users, and suppressed scattering. While the chamber and the precision robotics required for moving the AUT or probe comprise an expensive and expansive item, near-field systems offer extremely quick and convenient pattern measurement, which also allows rapid development iteration.

The near-field pattern measurement requires a calibration of the testing antennas (probes), and this is usually a manufacturer’s task, often recommended to be undertaken every few years to compensate for relative drift between the probes. While the directivity is available from the pattern, estimating the gain and efficiency still requires a calibration using a standard antenna. Standard antennas have a specified maximum gain, rather than a specified “standard pattern”. Their maximum gain is seldom specified to a bet-
There is a growing body of work on near-field measurement results, and computer-modeled studies (of the physical test system) for accuracy evaluation and sensitivity to aspects of the measurement configuration. The contributions range from pioneering work at the US National Bureau of Standards e.g., [2], to the body of results from measurement system manufacturers, such as that from van Rensburg (e.g., [3]) and Fogel (e.g., [4, 5]), and neutral “user experience” results such as [6, 7, 8, 9, 10, 11, 12]. Procedures for determining the measurement uncertainty for certain pattern types (such as high or low directivity) for near-field measurement configurations are established, e.g., [13, 14].

High directivity patterns used for satellite transmission usually have a specification for the relative gain in directions away from the main beam, in order to sufficiently suppress interference to other satellites. This emphasizes a need for accuracy over a wide dynamic range rather than just the maximum gain.

Low directivity patterns are used for mobile antennas. Under commonly-used, idealized conditions, the patterns themselves do not matter in the usual sense, since the distributed gain (Mean Effective Gain) of a single-port antenna is simply the radiation efficiency over two, e.g., [15]. But the complex pattern detail is still important for designing multiple-element antenna systems where patterns are sought that are orthogonal (uncorrelated) over the incident propagation distribution. The phase of the pattern is particularly important for this orthogonality. In short, basic measurement accuracy is critically important for both high directivity and low directivity patterns.

Finally, the role of simulation is important, because it has become the main design and analysis tool in antenna development. Patterns with extreme dynamic range are readily available from simulation, but the question always lingers as to whether they are "correct". The advantage of simulated patterns is not just their convenience but also their accuracy and repeatability for a given model. Although different simulation approaches provide variations for the same antenna model, using the same simulation software with the same antenna model should have perfect repeatability. Results can be checked for their model configuration stability by changing the discretization. For example, for FDTD type systems, varying the grid size and configuration usually indicates a convergence, and time-domain and frequency-domain solutions should yield very similar results.

The sources of inaccuracy, relative to a physical measurement, include potential errors in the antenna simulation model and its discretization, and also the fundamental difference between the structures used for simulation and the hardware of a physical measurement. Prototypes are often hand-fabricated with significant (relative to highly accurate pattern estimation) dimensional inaccuracy. If there is dielectric present, such as the substrate of a patch antenna, the complex permittivity is seldom known with high accuracy and it has a variation across different manufacturers and different production batches. A common approach has been to adjust the simulation complex permittivity in order to match pattern (or impedance) results to those of a physical measurement. Such an empirical approach usually ensures good agreement between simulation and measurement of course.

A physical measurement normally features a feed cable attached to the isolated antenna, and the cable presence normally influences the pattern. Including an electrically long cable (normally required for a pattern measurement) makes the simulation model electrically large and this can compromise the convenience and accuracy of the simulation. Also, the cable orientation, etc., can influence the measured pattern. For these reasons, feed cables are usually omitted in a simulation. In a physical deployment, the pattern is also influenced by proximate scattering, such as from its mounting platform. This can be a dominant feature, such as with cellphones, and a body of work is dedicated to in-situ type measurements, e.g., [16].

In this paper, a comparison of patterns and their parameters is made for low directivity antennas between two similar near-field measurement systems - both ranges are MVG Stargate - Satimo SG64 [17], but with different configurations. The SW facility is for up to 6GHz, and the SFU facility uses a second set of interleaved probes which are specified for up to 18GHz, although it has never been able to pass MVG’s own manufacturers calibration for above 16GHz.

The measurements were made of the same two-port antenna by different co-authors (MR for the SFU measurements, and AB for the SW measurements, see below), i.e., a realistic test for repeatability. Simulated patterns are included in the comparison. (The simulations and also the correlation calculations were undertaken by co-author MR.) While the comparison of simulation and measured patterns is a common feature in the literature, comparisons between different physical measurements for repeatability is rare [18]. A comparison of correlations from measurements is presented in [18] but this was checking the repeatability of decorrelation between patterns, rather than for repeatability of the basic pattern measurement, as presented here.

2 Measurement configuration

The results from the two pattern measurement facilities are labelled SFU (Simon Fraser University) and SW (Sierra Wireless Inc.). The Satimo SG-64 coordinate system, for both facilities, is shown in Fig. 1. The antenna under test
(AUT) is a dual patch antenna (see Fig. 2 right) with FR4 substrate. FR4 in fact represents a range of substrates from different manufacturers, with a range of complex permittivities. For simulation results and design, the substrate is taken to have $\varepsilon_r = 4.3$, $\tan \delta = 0.025$, and a thickness of 0.8 mm ($0.01\lambda_0 @ 5.7$ GHz). These antennas were tuned for the Unlicensed National Information Infrastructure (UNII) radio band covering Wi-Fi frequencies 5470 MHz to 5725 MHz (UNII-2C) and 5725 MHz to 5850 MHz (UNII-3).

![Figure 1. SG-64 Satimo coordinate system [19]. These co-ordinates usually need transforming to the coordinates of an antenna under test (AUT). The AUT sits on the white styrofoam column. The 64 probes are on the absorber-clad ring, and comprise crossed elements for dual polarization. In the SFU configuration, an extra set of probes are alternately placed for a higher frequency band. The column rotates for the azimuth variation, and the elevation variation is from multiplexed measurements from the multiple, fixed probes on the fixed ring.](image)

The calibration antenna for the SFU facility is a Satimo calibration horn antenna SH2000 (operates from 2 GHz to 32 GHz), and for the SW measurement, it is the SH400 (operates from 0.4 GHz to 6 GHz). Only the broadside gain from the horn is used for the calibration - the probe at the top of the probe ring (see Fig. 1) - is used for storing the complex amplitude, and the other probes are assumed to retain their complex gains relative to the topmost element, see Fig. 1. The manufacturer calibration, recommended every few years, is for ensuring that these stored relative gains are current, compensating for long-term drift.

3 Measurement results and discussion

This section presents the results from simulation and measurement from both facilities. The far-field measurement set-up in both SW and SFU is shown in Figures 2 and 3. On the left of Fig. 2 the VNA is shown connected to the dual port antenna inside the chamber, and on the right, the two-port AUT is shown. The impedance measurement is performed using a two-port Field-Fox Vector Network Analyzer (VNA) [20] and this measurement is undertaken inside the anechoic chamber which reduces scattering from surrounding objects relative to measurements outside of the chamber, for example on a laboratory bench.

In Fig. 3, the somewhat different mounting arrangements at the two measurement facilities are shown.

![Figure 2. AUT configuration for impedance measurement (left), simulation model and prototype (right) of the antenna (dual diversity patch antennas) with groundplane length (GL) = $1.1\lambda_0$, groundplane width (Gw) = $0.61\lambda_0$, patch width (W) = $0.25\lambda_0$, patch length (L) = $0.23\lambda_0$, feed position (f) = $0.07\lambda_0$, antennas spacing (d) = $0.26\lambda_0$ and FR4 substrate thickness of $0.01\lambda_0 @ 5.7$ GHz.](image)

![Figure 3. Configuration of the AUT for pattern measurement, for SFU (left) and for SW (right).](image)

Figure 4 illustrates the simulated and the measured s-parameter results for both antenna ports, at both of the facilities.

The simulated $S_{11}$ and $S_{22}$ indicate different resonant frequencies for the two antennas, intended for experiments with frequency diversity (see below). However, the hand-fabricated prototypes were re-tuned to have more similar resonant frequencies which were in between these.
The SFU - $S_{11}$ measurement is in the centre of the band. The SW-measured $S_{22}$ resonance coincides well with the simulation. For a narrowband patch antenna, this is fortuitous - there is usually a difference in the resonant frequencies between the simulated and the measured minima of the reflection coefficients because of the uncertainty of the complex dielectric constant of the substrate, as well as the usual differences between the simulation and prototype antennas, especially their feed detail. As indicated above, for patches, simulation resonant frequencies can usually be made to agree with measurements for patches by fiddling the simulation complex permittivity of the substrate. Of more interest is the significant difference between the resonant frequencies of the basic reflection coefficients between the two facilities. Moreover, the offsets of the frequencies are in different directions for the two facilities. These differences in these primary measurements between facilities reveal basic repeatability limits for these measurements. The measured resonance frequencies, or the -10dB bandwidths, are different by about 0.1 GHz, i.e., about 1.6%.

The $S_{21}$ parameters depend on $S_{11}$ and $S_{22}$ - the greater the reflection, the less the transmission between ports, so less can be inferred from the transmission parameters alone. The simulated $S_{21}$ is below the pair of measured $S_{21}$s, which can be expected since the simulated reflections are higher than the measured ones.

The pattern-derived parameters are now addressed. The simulated and the measured realized gain of antenna 1 and antenna 2 of the dual patch antenna are respectively in Figures 5 and 6; and the total efficiencies are in Figures 7 and 8.

The ripple of each curve, and the differences between the curves, indicate the uncertainty of these measurements. The maximum difference in realized gain within the operating frequency range, is almost 0.7dB, for antenna 1, at 5.51GHz. Similarly, the maximum difference in efficiency between the measurements is about 0.9 dB, again for an-
Figure 8. Simulated and measured total efficiency for antenna 2 of dual patches. Solid line: simulation, dotted line: measurement at SW and dashed line: measurement at SFU.

tenna 1, at about 5.51GHz. These are key findings for measurement repeatability.

Pattern cuts for the simulated and the measured patterns of antenna 1 and antenna 2, are plotted in Figures 9 and 10 respectively, for 5.7GHz. The left plots are for the $\phi = 0^\circ$ cut, the middle plots for the $\phi = 90^\circ$ cut, and the right plots for the $\theta = 90^\circ$ cut; with the top row (a) for the $\theta$ polarization and the lower row (b) for the $\phi$ polarization.

The patterns measured at both facilities have some ripple for both antennas, seen in the elevation cuts (left and centre plots). The most likely causes are the effect of the test cable, which was situated differently for each facility. Ferrite beads are used on the test cable in both chambers, although the beads and their precise placement were different. These suppress the currents flowing on the cable and thereby suppress some of the unwanted effect of the test cable. (But there will still be some scattering from the ferrite beaded cable.) The cables were placed according to different test-configuring procedures and habits at the different facilities, a typical real-world aspect of measurement repeatability. We do not expect these pattern ripples from a small-aperture antenna (as can be seen in the simulated patterns).

The measurements agree to within $\pm 0.8$dB in the directions of maximum (polarized) gain in the cuts, between the different facilities. In some other directions, particularly near pattern minima, the measured directional gains do not agree well at all.

The lower values of the cross-polar gain patterns: (a), top plot; (b), centre plot; are not in good agreement. For this polarization, the measurement SNR is effectively smaller, and the pattern estimation accuracy is degraded accordingly. Differences of 10dB can be found, and as noted, where there are pattern minima, there are much larger differences. These larger differences are at low power levels, and do not tend to impact the correlations as much as pattern differences in the high power directions.

Figure 9. Simulated (magenta solid line) and measured far-field radiation pattern at 5.7GHz. Measurements are taken in SW (red dotted line) and in SFU (blue dashed line) for antenna 1 of dual patches. (a) $\theta$ polarization (b) $\phi$ polarization. $\phi = 0^\circ$ (left), $\phi = 90^\circ$ (middle) and $\theta = 90^\circ$ (right).

Figure 10. Simulated (magenta solid line) and measured far-field radiation pattern at 5.7GHz. Measurements are taken in SW (red dotted line) and in SFU (blue dashed line) for antenna 2 of dual patches. (a) $\theta$ polarization (b) $\phi$ polarization. $\phi = 0^\circ$ (left), $\phi = 90^\circ$ (middle) and $\theta = 90^\circ$ (right).

One way to determine how similar the measured and the simulated patterns are, including in the directions away from the maximum gain, is to correlate them. The correlation coefficient (calculated using the same formula that is used for the Envelope Correlation Coefficient (ECC) [21, 22]) includes the phase of the patterns. The ECC pattern correlations between the simulated pattern and the measured pattern of antenna 1, and similarly for antenna 2, are plotted in Fig. 11. The correlation is well below unity, but the correlation of complex patterns is very sensitive to the pattern differences, especially the phase differences.

The correlation between the measured patterns from the two facilities is in Fig. 12, which includes the complex patterns and the power patterns. The power patterns, having “lost” their phase, have higher correlations. The authors are not aware of previous work that has presented a comparison in this way. So while it is not possible to compare this with previous work, it is a robust metric for pattern repeatability.

Finally, we look at the correlation function of antenna 1 and
antenna 2, against frequency, in Fig. 13. This is the ECC of the dual port antenna, as used in diversity applications. Here, low values of ECC are less sensitive to the pattern differences from different facilities. This type of plot is discussed in [18].

![Pattern correlation between measured and simulated far-field patterns for antenna 1 and antenna 2 of the AUT (measurements are from independent facilities, SFU and SW).](image1)

**Figure 11.** Pattern correlation between measured and simulated far-field patterns for antenna 1 and antenna 2 of the AUT (measurements are from independent facilities, SFU and SW).

![Pattern correlation between measured far-field radiation patterns from independent facilities (SFU and SW) for antenna 1 and antenna 2 of the AUT. For this plot the correlation of the complex amplitude patterns and also the power patterns (magnitude square, so no phase included) is shown.](image2)

**Figure 12.** Pattern correlation between measured far-field radiation patterns from independent facilities (SFU and SW) for antenna 1 and antenna 2 of the AUT. For this plot the correlation of the complex amplitude patterns and also the power patterns (magnitude square, so no phase included) is shown.

4 Summary

This paper backgrounds the issues of antenna pattern measurements, and contributes new results on repeatability. We compared patterns and their derived parameters, taken from similar, but independent, near-field measurement systems (both systems Satimo SG64 spherical scan, but with somewhat different configurations). We included pattern correlation results with a simulated pattern, and the correlations between the patterns measured at the different facilities. These offer a feel for the accuracy, as gauged by the correlation metric, from professional-grade facilities. The maximum gain measurement from both facilities follow the trend of the simulated gain relatively well, as expected. However, there is difference of up to about ±1dB in the gain and the efficiency from the two measurements. Large differences in the gain occur at some low-gain directions, particularly near minima, and these directions are the most challenging to get good pattern accuracy.

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References


