

On Gain Measurements Using the Substitution Method with UASs

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Abstract—Unmanned Aerial Systems (UAS) are a novel solution for antenna measurements. Due to their flexibility and portability, they are an ideal solution for in situ measurements of large antennas. However, measuring large antennas in situ, i.e., outdoors, introduces environmental errors due to wind, among others. The substitution method is an established approach to measure an Antenna Under Test’s (AUT) gain. The method is based on the knowledge of the gain of a reference antenna: the gain standard. However, this method relies on the mechanical precision of the acquisition system, since measurements not acquired exactly at the maximum of the main lobe of both antennas introduce error. This becomes especially critical for flexible positioner systems such as UAS. In this work, the gain of an offset parabolic reflector antenna, the AUT, is estimated using a Standard Gain Horn (SGH) through outdoor measurements. The gain estimated is compared to measurements performed in ESA-ESTEC’s facilities. The maximum of the main lobe is determined by performing a fine raster scan with the UAS in the AUT’s far field, which is then interpolated for the determination of the maximum. Then, that point is continuously scanned by the UAS for a certain time to compensate for errors introduced by in-flight vibrations due to the system itself and to external elements, such as wind gusts. In this work, the analysis to estimate the required measurement time, as well as its validation through measurements, are presented.

I. INTRODUCTION

Drone-based antenna measurement systems have gained increased attention and popularity in recent years [1]–[4] as an alternative to classical positioner systems and, especially, as a solution for outdoors, in situ measurements [5] and satellite testing [6]. The need of measuring in situ stems from a myriad of challenges, e.g., logistic problems to move an Antenna Under Test (AUT), sheer size of the AUT, need to validate the performance in the application environment, or need to validate that an AUT still is within specification after disassembling it for transport and mounting it again. Beside measurements of the radiation pattern, there is an increasing need of measuring the AUT’s gain in situ. However, the larger number of degrees of freedom UAS systems provide increases concerns about the positioning and pointing uncertainty mid-flight, especially when external influences are considered, such as the effect of constant wind, discrete wind gusts, or temperature drift. In this work, a method to generally estimate the influence of these effects and to calculate the adequate measurement time for gain substitution measurements using drone is introduced. The method is tested experimentally at QuadSAT’s facilities in Odense, Denmark, using QuadSAT’s UAS for Antenna Pattern Evaluation (UAS-APE) system. As AUT, an offset dish antenna, MVG’s SR-40, is used. This antenna has been previously characterized at ESA-ESTEC’s facilities [5] and



Fig. 1: QuadSAT’s compact UAS-APE. The compact gimbaled remote source antenna can be seen situated under the drone.

the provided gain value is used as reference. As Standard Gain Horn (SGH), a pyramidal horn antenna characterized at Technical University of Denmark (DTU) is used. To find the main beam’s peak of each antenna, a raster scan is performed with the UAS-APE system, followed by a single-point measurement of a certain duration at the peak. The duration is calculated with the introduced method. Finally, the gain substitution method is applied and the gain obtained for the AUT is compared to the gain measured at ESA-ESTEC’s facilities to derive the measurement uncertainty, and compare it to the predicted uncertainty. In Section II, the UAS-APE system is introduced. The substitution method for the measurement of gain is introduced in Section III, as well as the measurement procedure and the expected error sources. Section IV handles the estimation of the measured time based on the already-introduced error sources, and experimental results are shown in Section V. Finally, conclusions are drawn in Section VI.

II. UNMANNED AERIAL SYSTEM FOR ANTENNA PERFORMANCE EVALUATION (UAS-APE)

QuadSAT’s UAS-APE, shown in Fig. 1, replaces the positioner of traditional measurement chambers with a drone platform. A pre-flight path plan is generated using advanced flight controller together with the company’s proprietary software, and the controller follows the path plan rejecting environment disturbances and adjusts drone and propellers velocity. The RF payload contains the measurement probe and adjusts orientation with the navigation data it receives from the drone platform, thus ensuring an orientation perpendicular to the scanning sphere’s surface.

A. RF Payload

The RF payload mounts a dual-polarized quad-ridged horn as measurement probe operating from 6 GHz to 24 GHz,

and works in transmit mode. To enable this, a dual-channel signal source is used. The probe is mounted on a 3-axis (yaw-pitch-roll) stabilized gimbal, which corrects orientation with the help of several sensor [5]. Additionally, the RF payload contains a 10 MHz GPSDO frequency reference for the calculation of the UAS position.

B. Ground Control Station

The role of the Ground Control Station (GCS) is to act as a receiver for the AUT and to process both measurement data and positioning data. It comprises a receiver system, a main computer and a Real Time Kinematics (RTK) station. Through a communication module, the RTK provides positioning error corrections to the UAS-APE. The main computer and the RTK corrections, together with the GPS receiver on the UAS unit, form a Differential Global Positioning System (DGPS) solution. The current RTK system ensures a UAS position accuracy of 2 cm horizontally and 5 cm vertically. Taking this into account, the UAS-APE and DGPS system achieve a position uncertainty for the UAS limited to a cube of 30 cm edge surrounding the drone, in conditions of wind of up to 15 m/s (33 mph or 54 km/h). The input from the receiver is combined post-flight with drone navigation data by the main computer, referenced to GNSS time.

III. GAIN MEASUREMENTS THROUGH SUBSTITUTION

In this work, the substitution method is used to measure the gain of an AUT using an UAS-APE system. The field value of the Standard Gain Horn's (SGH) main beam, measured at its maximum, is compared to the main beam's maximum of the AUT. From the known gain of the SGH, the gain of the AUT is derived following the formula

$$G_{\text{AUT}}(\text{dBi}) = E_{\text{max, AUT}}(\text{dB}) - E_{\text{max, SGH}}(\text{dB}) + G_{\text{SGH}}(\text{dBi}), \quad (1)$$

where $E_{\text{max}}(\text{dB})$ is the field value measured at the maximum of the main beam of each antenna and under the assumption of a unique main beam oriented towards the direction of propagation. The beam finding is performed with a raster scan and, once the maximum of the main lobe is retrieved, the UAS-APE performs a continuous measurement of that point for a certain duration.

A. Outdoor range at QuadSAT's facilities

Outdoor measurements were performed at QuadSAT's facilities at Hans Christian Andersen airport in Odense, Denmark. The AUT and the SGH are mounted on a 3-axis manual tripod, placed on the ground with a certain pointing angle in elevation, and a receiver is connected to it. The UAS-APE system works in transmit mode. The measurement distance chosen for the gain measurements shown is $r = 350$ m. There is no fixed geometrical reference in the used range: the alignment is performed electrically, which allows the system to stay flexible.

B. Alignment: Raster Scan

As mentioned in the previous subsection, the alignment is performed electrically, aligning the coordinate system with the electrical boresight of the AUT. This is done by performing a raster scan. A raster scan is a series of

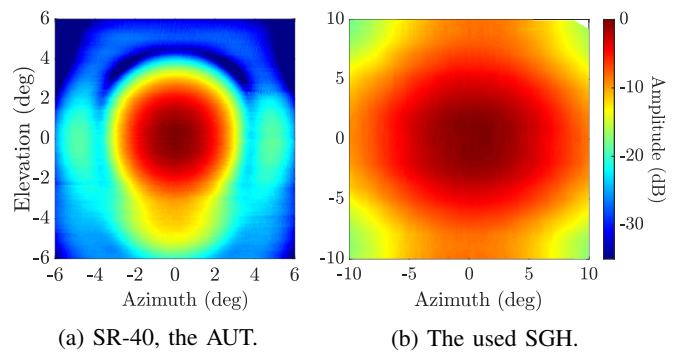


Fig. 2: Measured raster scans.

azimuth cuts acquired over a range of elevation angles in an azimuth-over-elevation coordinate system. The trigger is continuously activated during flight and the resulting data does not conform to a regular grid. The data is interpolated to an equispaced grid and, afterwards, the maximum of the main beam is calculated and used as reference. In Fig. 2, raster scans measured for the AUT and the SGH are shown, with the amplitude presented in the form of a false-colour checkerboard plot. The patterns are presented on a regular azimuth over elevation grid in an angular range about the boresight direction.

C. Error Sources and Measurement Time

To accurately estimate gain using the substitution method, it is important that the value of the maximum of the main beam of each antenna, namely the AUT and the SGH, be measured accurately. Due to the nature of UAS measurements, however, different factors hinder the measurement, such as the effect of wind gusts [7] and vibrations on both the UAS and the AUT, probe misalignment due to wind, and drift. While the wind-related uncertainties, modelling wind with a normal distribution [8], are mitigated by increasing the number of measured samples and, as such, the measurement time, the uncertainty introduced by drift increases with the measurement time. This leads to a compromise: measurements shall be long enough for the errors due to environmental conditions to be mitigated, but as short as possible to reduce drift.

1) *Effect of Wind Gusts and Vibrations:* The effect of wind gusts and vibrations is, for the most, random. The position uncertainty caused by wind and vibrations is defined by a box with dimensions $30 \text{ cm} \times 30 \text{ cm} \times 30 \text{ cm}$ surrounding the UAS due to wind influencing the drone out of its programmed flight plane [5]. This is considered to be the 3σ uncertainty. However, the effect of wind-gusts-induced vibrations on the AUT are more difficult to characterize.

2) *Probe Misalignment Due to Wind:* While wind indeed introduces an error in probe alignment, the used probe's directivity is much lower than most antenna's measured with this technique, which are typically large, high-gain antennas. Therefore, it is considered that the error introduced by probe misalignment is negligible in comparison to other error sources for the approach used in this work.

3) *Drift:* An average value for drift has been derived in previous works [5], and is reused for convenience. The used value is $\text{Drift} = 0.006 \text{ dB/min}$.

IV. ESTIMATION OF THE REQUIRED MEASUREMENT TIME

The calculation of the measurement time is done by estimating the variance of a measurement affected by the error sources introduced in Subsection III-C and, thereafter, calculating the number of samples required to make it converge to its mean with an error smaller than a given threshold. The variance of the measured signal, beside depending on the used UAS and on the wind at the time of the measurement, is antenna-specific, since a given angular uncertainty delivers different measured values depending on the beamwidth of the AUT.

A. Estimation of the Beamwidth and Angular Deviation

The followed approach is a worst-case estimation to retrieve the standard deviation of the measurement value, from which the variance is calculated and used to model the measurement values as a normal distribution. The calculation of the expected angular deviation starts from a coarse assumption of the AUT gain based on its physical size, and the 3 dB beamwidth, for an expected efficiency $\eta = 0.5$, is then estimated solving the empirical equation [9]

$$G \approx 10 \log_{10} \left(\frac{27000}{\theta_{3 \text{ dB},1} \theta_{3 \text{ dB},2}} \right), \quad (2)$$

where G is the AUT gain, and $\theta_{3 \text{ dB},1}$, $\theta_{3 \text{ dB},2}$ are the 3 dB beamwidth measured on the principal planes. Assuming a perfectly symmetric main lobe, $\theta_{3 \text{ dB},1} = \theta_{3 \text{ dB},2} = \theta_{3 \text{ dB}}$ and solving (2) for an assumed gain G yields

$$\theta_{3 \text{ dB}} \approx \sqrt{\frac{27000}{10^{G/10}}}. \quad (3)$$

Following Subsubsection III-C1, it can be assumed that the UAS will keep itself within a box with dimensions $30 \text{ cm} \times 30 \text{ cm} \times 30 \text{ cm}$. Taking the middle of the box as the correct position, the worst case, i.e., the furthest position from the center within the box, is $a = \sqrt{(15 \text{ cm})^2 + (15 \text{ cm})^2 + (15 \text{ cm})^2} = 26 \text{ cm}$ away from the center. For a given distance from the AUT r , the angular variation α can be estimated by

$$\alpha = \arctan \frac{r}{a} - \pi/2. \quad (4)$$

The obtained angular variation α , however, only includes the normal wind and vibration effects affecting the UAS, and does not include any misalignment of the AUT caused by wind-induced vibrations. For the sake of a worst-case estimate, it is considered that discrete wind gusts may increase the angular variation by a factor $k = 3$, and that the AUT suffers from the same variation. The worst case is, then, that AUT and UAS be affected by this expanded angular variation in opposite directions, thus delivering an effective total angular variation of $\alpha_{\text{eff}} = 2k\alpha$. For the estimation of the signal variance σ^2 , the main lobe is modelled as perfectly symmetric, so that a single 1D cut can be modelled as a parabola of the form $y = Ax$, with

$$A = \frac{3}{(\theta_{3 \text{ dB}}/2)^2}, \quad (5)$$

so that the signal variation \tilde{s} for a given angular variation α_{eff} is calculated as $\tilde{s} = A\alpha_{\text{eff}}^2$. This variation is considered

to be the 3σ uncertainty of the signal, so that the standard deviation $\sigma = \tilde{s}/3$ is obtained and, thus, the variance σ^2 .

B. Estimation of the Measurement Time Through Monte Carlo Simulations

A Monte Carlo simulation is performed for a normal distribution with the calculated variance σ^2 , computing N experiments and redrawing all random variables between each of them. The number of samples i that achieves a difference Δ between the cumulative mean \bar{s}_i and the mean \bar{s} , lower than a threshold T , $\Delta = \bar{s}_i - \bar{s} < T$, is calculated as the mean of the result obtained from each experiment. The measurement time is finally calculated by dividing the number of samples obtained by the sampling rate.

V. EXPERIMENTAL RESULTS

The approach introduced in Section IV is applied to both the chosen AUT, the offset dish antenna MVG's SR-40, with a gain measured at ESA-ESTEC as $G_{\text{AUT}} = 33.05 \text{ dBi}$; and the SGH, a pyramidal horn calibrated at DTU, with given gain $G_{\text{SGH}} = 24.319 \text{ dBi}$. The considered measurement distance is $r = 350 \text{ m}$, and the tests are performed at $f = 14.5 \text{ GHz}$. For both antennas, a coarse gain estimation is done to apply in (4) and, from the resulting 3 dB beamwidth $\theta_{3 \text{ dB}}$, the standard deviation σ and the measurement time t_{meas} are retrieved with the introduced Monte Carlo approach. For the Monte Carlo approach, a number of experiments $N = 10000$ and a threshold of $T = 0.01$ are used. Finally, the measurement time is estimated considering a sampling rate of $f_s = 8 \text{ Hz}$. The initial estimations, partial results and resulting measurement duration are shown in Table I.

	G (dBi)	$\theta_{3 \text{ dB}}$ (deg)	σ (dB)	t_{meas} (s)
AUT	40	1.64	≈ 0.1	≈ 73
SGH	25	9.2402	≈ 0.003	≈ 12.5

TABLE I: Estimations for both the AUT and the SGH.

The reduce the effect of drift, the measurements, including the alignment raster scans, have to be performed as temporally close to each other as possible. The used test plan is:

- raster scan for alignment on the AUT ($\approx 20 \text{ min}$),
- measurement at the peak of the AUT's main beam for $t_{\text{meas}} = 73 \text{ s}$,
- raster scan for alignment on the SGH ($\approx 20 \text{ min}$),
- measurement at the peak of the SGH's main beam for $t_{\text{meas}} = 12.5 \text{ s}$.

Processing the measurements and applying (1) yields an estimated gain of the AUT of $\hat{G}_{\text{AUT}} = 32.91 \text{ dBi}$ and, thus, an absolute error of $\epsilon = -0.14 \text{ dB}$. For the calculation of the drift, the beginning of the actual gain measurements, i.e., the measurement at the peak of the AUT's main beam, is the relevant starting point. In total, the drift is accumulated for $\approx 30 \text{ min}$, so that, for $\text{Drift} = 0.006 \text{ dB/min}$ [5], the total drift amounts to $\text{Drift} = 0.18 \text{ dB}$, being the error reported within this uncertainty.

G_{SGH} (dBi)	G_{AUT} (dBi)	\tilde{G}_{AUT} (dBi)	ϵ (dB)
24.319	33.05	32.91	-0.14

TABLE II: Summary of the results.

VI. CONCLUSION

An approach to measure gain using the substitution method with UASs is introduced, together with a method to estimate the minimum required measurement time for an accurate measurement. The method aims at estimating the variance of the signal with worst-case estimates of the errors introduced by the uncertainty in the drone positioning and the effect of wind. Thereafter, the number of samples that makes the mean of a normally distributed signal with the calculated variance converge to its true mean, within a given threshold, is calculated by applying a Monte Carlo approach. From the number of samples, the measurement time is easily calculated for a known sampling rate. By keeping the measurement time short, the proposed method reduces the effect of drift, critical in outdoor measurements. Experimental results on well-characterized antennas show that outdoor measurements of an antenna's gain with an absolute error $|\epsilon| < 0.15$ dB are possible, while keeping the uncertainty introduced by drift, according to introduced model, limited and the error, within it.

REFERENCES

- [1] T. Fritzel, R. Strauß, H.-J. Steiner, C. Eisner, and T. Eibert, "Introduction into an uav-based near-field system for in-situ and large-scale antenna measurements (invited paper)," in *2016 IEEE Conference on Antenna Measurements Applications (CAMA)*, 2016, pp. 1–3.
- [2] L. Washburn, E. Romero, C. Johnson, C. Gotschalk, and B. Emery, "Antenna calibration for oceanographic radars using aerial drones," in *2016 IEEE Conference on Antenna Measurements Applications (CAMA)*, 2016, pp. 1–4.
- [3] M. García-Fernández, Y. Álvarez López, A. Arbolea, B. González-Valdés, Y. Rodríguez-Vaqueiro, M. E. De Cos Gómez, and F. Las-Heras Andrés, "Antenna diagnostics and characterization using unmanned aerial vehicles," *IEEE Access*, vol. 5, pp. 23 563–23 575, 2017.
- [4] G. Virone, A. M. Lingua, M. Piras, A. Cina, F. Perini, J. Monari, F. Paonessa, O. A. Peverini, G. Addamo, and R. Tascone, "Antenna pattern verification system based on a micro unmanned aerial vehicle (uav)," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 169–172, 2014.
- [5] C. Culotta-López, S. Gregson, A. Buchi, C. Rizzo, D. Trifon, S. Skeidsvoll, I. Barbary, and J. Espeland, "On the uncertainty sources of drone-based outdoor far-field antenna measurements," in *Antenna Measurement Techniques Association Symposium (AMTA)*. IEEE, 2021.
- [6] J. Espeland and A. Buchi, "How drone technology will revolutionize satellite antenna testing," *Microwave Journal*, August 2020. [Online]. Available: <https://www.microwavejournal.com/articles/34411-how-drone-technology-will-revolutionize-satellite-antenna-testing>
- [7] B. H. Wang, D. B. Wang, Z. A. Ali, B. T. Ting, and H. Wang, "An overview of various kinds of wind effects on unmanned aerial vehicle," *Measurement and Control*, vol. 52, no. 7-8, pp. 731–739, 2019. [Online]. Available: <https://doi.org/10.1177/0020294019847688>
- [8] A. H. Monahan, "The gaussian statistical predictability of wind speeds," *Journal of Climate*, vol. 26, no. 15, pp. 5563 – 5577, 2013. [Online]. Available: <https://journals.ametsoc.org/view/journals/clim/26/15/jcli-d-12-00424.1.xml>
- [9] J. E. Hill, "Gain of directional antennas," 1976.