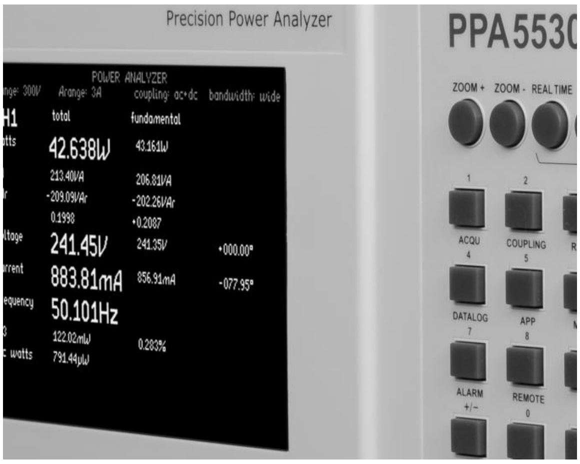
A technical overview of ranging techniques and the importance of Calibration.
N4L's modern approach to measurement.



What we will discuss in this technical paper;

- **How Peak Ranging offers many advantages over RMS Ranging**
- **The difficulties experienced extracting phase angle data from complex waveforms using analogue multipliers**
- **How accuracy is derived from the Reading and Range error**
- **The importance of calibration over the entire bandwidth of the instrument**

As Power Analyzer designers, one of the many decisions required in the early stages of the design process is - Should we RMS or Peak range?

In common with many issues a designer must consider, the argument for any specific approach to ranging is dependent upon many questions, including the nature of applications into which a measurement instrument is targeted and design details of the selected technique. It would therefore be completely wrong to suggest that one or other method is inherently more accurate than another without an understanding of these facts. Sadly, the objective of many marketing documents is to confuse rather than to clarify, so in this document, we aim to focus on the technical merit of options available to an engineer.

RMS Ranging Systems Explained

An RMS ranging system commonly utilises analogue multipliers or topology representing a similar approach. These techniques are well known, benefit from relative simplicity and are well suited to measurements that do not require precise measurement of phase angle or harmonic content of a distorted waveform. There is also the advantage for an instrument designer that an analogue multiplier system will simplify -

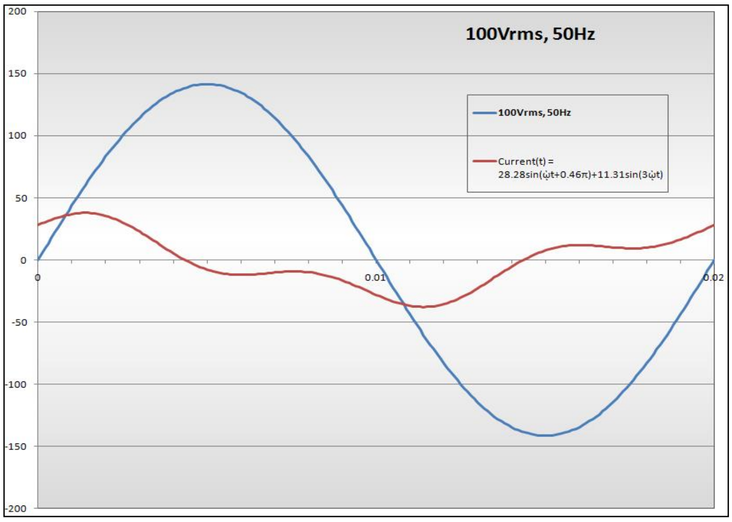


Fig 1

the digital processing stage of their design. Indeed, analogue multiplier IC manufacturers state themselves that digital solutions (i.e. peak ranging coupled with real time acquisition of V & I) offer greater sensitivity and dynamic range but the processing power required is much larger than analogue multiplication.

So, with limited processing power, an analogue multiplier based RMS ranging system would be the natural choice and many instrument manufacturers use this approach. However, if processing power is not a limitation, it is clear that a real time fully digital system may be preferable.

Significant advances over recent years in the performance / cost ratio of digital devices provide modern designers with options that were not previously available. It is now possible to achieve a level of performance and functionality that more conventional designs cannot achieve. The power analyzer range from N4L are an example of this, using the latest FPGA processors combined with modern DSP devices to achieve a level of real time processing power that cannot be matched by the conventional techniques still used in many products available today.

Further detail on the measurement of phase angle via analogue multiplier or fully digital techniques: In most cases, analogue multiplier based power analyzers calculate phase angle from the quotient of W and VA (W/VA) or in some cases, direct measurement based upon zero crossover detection. Whilst these techniques are suitable for a perfect sine wave, most users face the reality that perfect sinewaves are very rarely seen in a modern power electronics environment. In fact, the only environment in which we can expect a truly sinusoidal waveform is within a calibration laboratory, so, a measurement system utilising such a technique will not be the ideal solution for a wide range of power measurement applications. In contrast, fully digital systems that are able to derive both phase and harmonic data without dependency on the signal waveshape offer a clear advantage in most real world applications.

Accuracy

Some manufacturers utilising the RMS ranging approach have claimed that "RMS ranging offers greater accuracy". This statement is fundamentally wrong and is based upon an incorrect assumption that the percentage range error of both RMS and Peak ranging systems are the same. This makes no more sense than to argue that a car with bigger wheels will always be faster than a car with smaller wheels.

To illustrate using REAL product data, let us consider the following scenario (the waveform in fig 1);

Voltage Waveform:
100Vrms, Crest Factor = 1.41, (Peak = 141V), Frequency = 50Hz

When a 100Vrms signal with a crest factor of 1.41 is measured, N4L instruments will automatically select the 300Vpk range. The range error of the PPA5500 series power analyzer is 0.038% @ 50Hz and the reading error is 0.01%. Note: On the vast majority of measurement instruments, the range error is the dominating error component.

N4L PPA5500 Peak Ranging Error (Voltage)

The error in the measurement broadly comprises of the reading error plus the range error (we will ignore the frequency component as this should have negligible effect at frequencies below 1kHz in any good quality power analyzer).

PPA5500 Voltage Accuracy Spec (Peak Range)

Voltage Reading	Instrument Range (Peak ranging system)	Instrument Range Error %	Instrument range error V	Instrument reading error %	Instrument reading error V	Total error V	**Total error %**
100Vrms (141Vpk)	300Vpk	0.038%	0.114V	0.01%	0.01V	0.124V	**0.124%**

Table 1

Typical RMS Range Error (Voltage)

In the table below we display a typical competitive accuracy specification for an RMS ranging instrument. It can be seen that due to the differing reading and range error specifications of this product which competes directly with the PPA5500, the total accuracy of the competitive instrument remains inferior, despite selecting in our example a voltage that is optimum for accuracy on the RMS range system.

Typical competitor RMS Range Specification (Voltage)

Voltage Reading	Instrument Range (RMS ranging system)	Instrument Range Error %	Instrument range error V	Instrument reading error %	Instrument reading error V	Total error V	**Total error %**
100Vrms (141Vpk)	100Vrms	0.05%	0.05V	0.1%	0.1V	0.15V	**0.15%**

Table 2

Note 1: We use the example of 100V to illustrate a worst case comparison where the PPA is on a higher range than an RMS based system. If we used an example of 230Vrms, the PPA accuracy benefit would have been more significant (0.0575% vs. 0.1625%).

Note 2: The quoted accuracy of many measurement instruments is less than 1 year. Care should therefore be taken to add the additional error associated with a full 1 year specification if this period is required. All N4L specifications apply for 1 year.

Overview of Accuracy

As we have illustrated, in order to compare peak range accuracy with RMS range accuracy the actual reading and range error percentages for the respective instruments must be considered.

RMS ranging exhibits drawbacks associated with phase angle calculation of distorted waveforms as well as the mythical claims of improved accuracy.

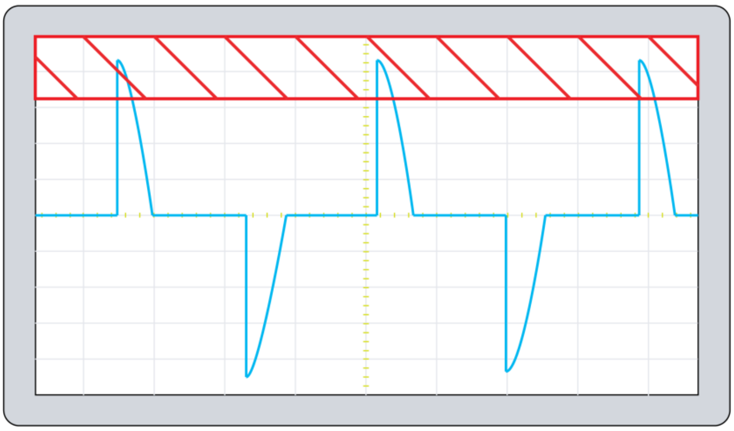
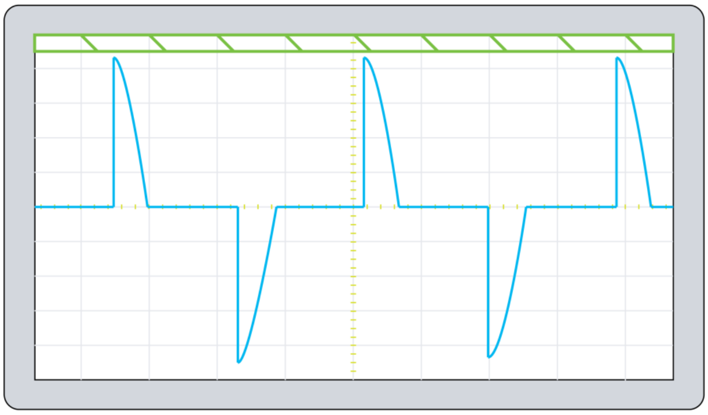


Fig 2. Example of waveform clipping with RMS range fixed CF

What about clipping?

In many applications, the crest factor of the signal being analysed will be unknown or the crest factor will be very high. RMS ranging systems function upon preset Crest Factor configurations, the highest crest factors seen on RMS ranging systems are typically around CF6, this is simply not high enough for modern power electronic waveforms and crest factors higher than CF10 are commonly seen, as stated in the EN50564 Standby Power Standard.

Fig 3. High CF waveform with peak



Waveform clipping is an issue that must be avoided in order to digitise (or multiply in the case of an analogue multiplier) the entire signal. This approach leads to increased range error for the same RMS range value when a higher crest factor is set on the instrument (such as 6).

What this increased error factor hides is the fact that the instrument has effectively doubled its **peak** range. Note we mention, **peak** range for an RMS instrument - this is a key point as ultimately the RMS ranging instrument MUST include the peak and one cannot assume that the headline specification of an RMS ranged instrument is what they will achieve, since any waveform with a crest factor above defined thresholds will result in reduced accuracy.

The N4L proprietary ranging system is able to automatically detect peak levels and will maintain full standard accuracy at crest factors up to a value of CF20, therefore supporting all major application sectors. For any unusual application that could require a crest factor higher than this, N4L power analyzers can be manually ranged and provide a dynamic range equal to a crest factor of 300.

Phase measurement of complex waveforms

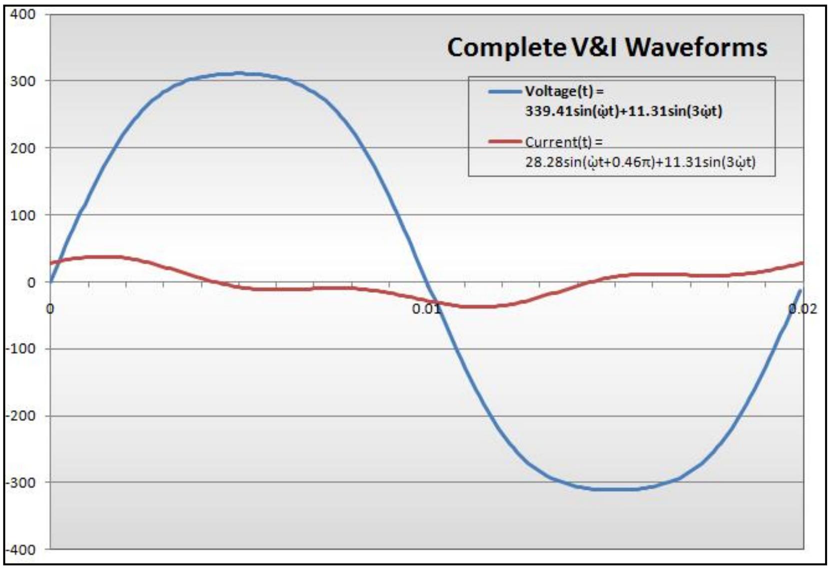


Fig 4

Precise measurement of phase angle is a critical factor in any power measurement, whether it is the Watt loss analysis of a low frequency low power factor load or the high frequency Watt error of a harmonically distorted load. The techniques utilised by N4L result in excellent phase accuracy, this is achieved by a combination of both very "flat" analogue design and a digital phase measurement system that maintains accuracy in the presence of noise or distortion.

Conversely, analogue multiplier systems are poor or in some cases incapable, of achieving accurate fundamental or harmonic measurements in the presence of noise or distortion. We will look at how the analogue multiplier suffers from the assumption of a sinusoidal waveform.

Phase computation

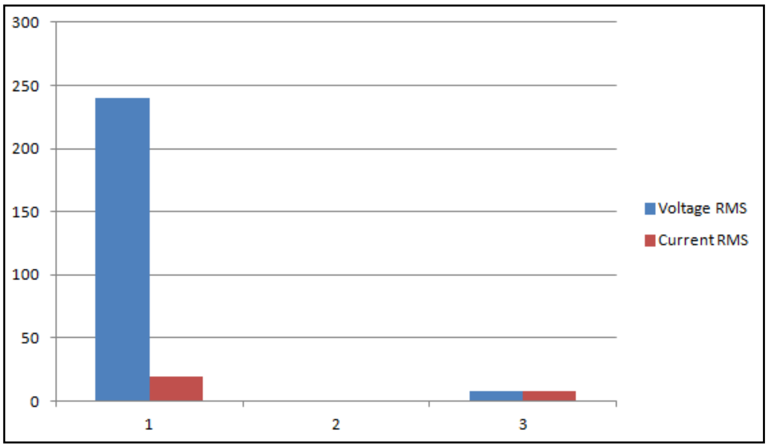
The waveforms below were used in the following example;

$$v(\mathrm{t}) = 339.41\sin(\omega\,\mathrm{t}) + 11.31\sin(3\,\omega\,\mathrm{t}) \qquad i(\mathrm{t}) = 28.28\sin(\omega\,\mathrm{t} + 0.46\,\pi\,) + 11.31\sin\,(3\,\omega\,\mathrm{t})$$

Waveform harmonic content

Harmonic	Voltage RMS	Current RMS
1	240	20
2	0	0
3	8	8
4	0	0

Table 3



For the purpose of this example, we will consider an RMS measurement with zero analogue error, which is clearly not possible in practice but allows us to illustrate primary obstacles associated with analogue multiplier phase measurement from a fundamental mathematics point of view.

Deriving the RMS Voltage and Current from the following functions;

For a sampled signal $\mathrm{rms} = \sqrt{\left[\frac{1}{\mathrm{n}} \sum_{i=0}^{i=n-1} v^2[\mathrm{i}]\right]}$

Pure Mathematical Harmonic rms = $\mathrm{rms} = \sqrt{[\mathrm{h}1^2 + \mathrm{h}2^2 + \mathrm{h}3^2 \ldots..\mathrm{h}^2]}$

Using a fundamental mathematical approach for an RMS ranging system (Analogue Multiplier);

Vrms = 240.133V Irms = 21.541A VA = 5172.704 Watts = 761.6W

Power Factor = W/VA = 0.147 Phase Angle = $\cos^{-1} 0.147 = 81.547\ degrees$

If we compare this phase shift to the original functions of voltage and current, we can see that the phase shift is 0.46π on the fundamental component

$$0.46\pi = 82.8\ degrees$$

This has resulted in a 1.267 degree phase error of the fundamental component by using an analogue multiplier (W/VA) phase computation approach, compare this to N4L's 0.005 degree phase angle specification which is achievable as a result of implementing proprietary phase detection techniques, there is no comparison (0.005 degrees is conservative and will be compared to typical values later in the document).

Calibration

Whilst a brochure may quote headline accuracy specifications, it can often be the case that much of the frequency range of the power analyzer is specified without calibration and manufacturers will use characterisation methods in order to project the response of an instrument at higher frequencies. N4L have spent a great amount of time developing a calibration system that is able to directly calibrate an instrument over its entire bandwidth, which in the case of a PPA5500 power analyzer, is DC and 10mHz to 2MHz.

Typical Performance of **Low Frequency Voltage Calibration** (15 x N4L PPA5500 assessed)

Frequency	Applied Voltage	Measured Voltage	Voltage Deviation	Published Spec	Uncertainty	Safety Factor Including Uncertainty
55Hz	7.0000V	7.0002V	0.0029%	0.08%	0.007%	8.08
400Hz	7.0000V	6.9999V	0.0014%	0.08%	0.009%	7.69
850Hz	7.0000V	7.0003V	0.0043%	0.08%	0.008%	6.5
55Hz	220.00V	219.99V	0.0045%	0.06%	0.005%	6.3
400Hz	220.00V	220.02V	0.0090%	0.06%	0.007%	3.75
850Hz	220.00V	219.97V	0.0136%	0.06%	0.007%	2.9

Table 4

It should be noted that a calibration report is of little significance without stating the uncertainty of the calibration system, as illustrated in the limited extract above from our extensive calibration report you can see that the uncertainty of the system is well below the published specification and at many calibration points the PPA5500 provides far lower error than the uncertainty in the calibration system itself. This is significant as the calibrator used was a Fluke 6105A, the highest specification power standard on the market. The calculated safety factors include in the calculation any uncertainty of the calibration system, this is vitally important as uncertainty in a calibration system can in some cases exceed some manufacturers published accuracy rendering it meaningless.

$$Safety\ Factor = \frac{Published\ Spec}{(Deviation + Uncertainty)}$$

Typical Performance of **Low Frequency Current Calibration** (15 x N4L PPA5500 Assessed)

Frequency	Applied Current	Measured Current	Current Deviation	Published Spec	Uncertainty	Safety Factor Including Uncertainty
55Hz	700.00mA	700.11mA	0.0157%	0.08%	0.007%	3.52
400Hz	700.00mA	700.13mA	0.0186%	0.08%	0.009%	2.8
850Hz	700.00mA	700.16mA	0.0229%	0.08%	0.009%	2.5
55Hz	20.00A	19.995A	0.0250%	0.07%	0.007%	2.1
400Hz	20.00A	19.997A	0.0150%	0.07%	0.009%	2.9
850Hz	20.00A	19.992A	0.0400%	0.07%	0.009%	1.42

Table 5

The example data in table 5 illustrates the exceptional performance of the PPA5500, the data was collated from 15 separate power analyzers and represents typical performance.

Power Calibration

In order to carry out a complete calibration of the power analyzer voltage, current and phase must be verified. N4L perform calibration of all 3 of these parameters along with the calibration of power as a calibration parameter in its own right.

Typical Performance of **Power Calibration** (15 x N4LPPA5500 @ 220V 7A Assessed)

Frequency	Applied Power	Measured Power	Power Deviation	Published Spec	Uncertainty	Safety Factor Including Uncertainty
40Hz	1.5400kW	1.5399kW	0.0065%	0.1%	0.012%	5.4
55Hz	1.5400kW	1.5401kW	0.0065%	0.1%	0.008%	6.8
150Hz	1.5400kW	1.5399kW	0.0065%	0.1%	0.012%	5.4
400Hz	1.5400kW	1.5402kW	0.0130%	0.1%	0.012%	4
850Hz	1.5400kW	1.5402kW	0.0130%	0.1%	0.012%	4

Table 6

Phase Calibration

As stated, phase calibration is vitally important and it is a particular strength of the N4L power analyzers. Phase is calibrated at various phase angles and an extract of the standard calibration procedure is shown in table 7.

Typical Performance of **Power Calibration at Various Phase Angles** (15 x N4LPPA5500 @ 220V 7A Assessed)

Frequency	Applied VA	Phase	Applied Power	Measured Power	Power Deviation	Published Spec	Uncertainty	Safety Factor Including Uncertainty
55Hz	3.300kVA	0.000°	3.300 kW	3.2997kW	0.0091%	0.11%	0.009%	6
55Hz	3.300kVA	-30.00°	2.8579kW	2.8578kW	0.0035%	0.13%	0.009%	10.4
55Hz	3.300kVA	+45.00°	2.3335kW	2.3333kW	0.0086%	0.15%	0.010%	8
55Hz	3.300kVA	-60.00°	1,6500kW	1.6501kW	0.006%	0.20%	0.012%	11.1

Table 7

Typical Performance of **Phase Calibration at Various Phase Angles** (15 x N4LPPA5500 @ 220V 1A)

Frequency	Applied Voltage	Applied Current	Applied Phase	Phase Deviation	Published Spec	Uncertainty	Safety Factor Including Uncertainty
55Hz	220V	1.000A	0.000°	0.000°	0.006°	0.003°	2
55Hz	220V	1.000A	+30.00°	+0.001°	0.006°	0.003°	1.5
55Hz	220V	1.000A	+60.00°	-0.001°	0.006°	0.003°	1.5
55Hz	220V	1.000A	+90.00°	+0.001°	0.006°	0.003°	1,5

Table 8

High Frequency Calibration

We have developed a calibration process that combines the use of reference instrumentation calibrated to ISO17025 and custom design signal generation equipment. This gives N4L the ability to calibrate the entire frequency range of the instrument, whilst you may think that all power analyzers are calibrated throughout their entire frequency range, this is all too often not the case.

Typical Performance of **High Frequency Voltage Calibration** (15 x N4L PPA5500 assessed)

Frequency	Applied Voltage	Measured Voltage	Deviation	Published Spec	Uncertainty	Safety Factor Including Uncertainty
48kHz	203.94V	203.99V	0.0245%	0.36%	0.133%	2.2
220kHz	44.561V	44.589V	0.0628%	0.97%	0.438%	1.9
700kHz	9.7790V	9.8117V	0.3344%	2.92%	1.071%	2
1.2MHz	1.7627V	1.7640V	0.0738%	5.39%	0.704%	6.9
2MHz	1.6033V	1.6044V	0.0686%	8.27%	1.131%	6.8

Table 9

Table 9 offers a clear picture of the performance of the PPA5500 at high frequencies, the published accuracy specification of the PPA5500 at high frequencies is commonly regarded to be the highest on the market* and yet the safety factors including system uncertainty are very conservative and should give any user the confidence that the measurements they make are always in fact far more accurate than an already very good published specification. It should be noted that the table above is only a small extract from the full calibration certificate in which many more points on both the voltage and the current inputs are tested. The figures above are what we term at N4L as a "Final Electrical Verification" and are in fact verification points selected in between the original adjustment points offering a true picture of the linearity of the instrument and the integrity of the wideband response post adjustment.

Conclusion

Calibration and Ranging are topics steeped in mystery and we hope that this paper has provided clarity on some finer details of both. An engineer intending to purchase a power analyzer should be critical of any manufacturer that cannot supply a clear specification together with calibration data that illustrates a meaningful safety margin against correctly derived uncertainty values. Ideally, such data should cover the complete frequency range over which the instrument of interest is specified. The nature of a ranging system used within an instrument has no direct bearing on the accuracy that is provided. Accuracy should only be derived from the full specification of the associated instrument.

When correctly implemented, a peak ranging approach offers many practical benefits over an RMS ranging system with no compromise.