Novel Techniques of RF High Power Measurement

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EE PhD Dissertation Defense
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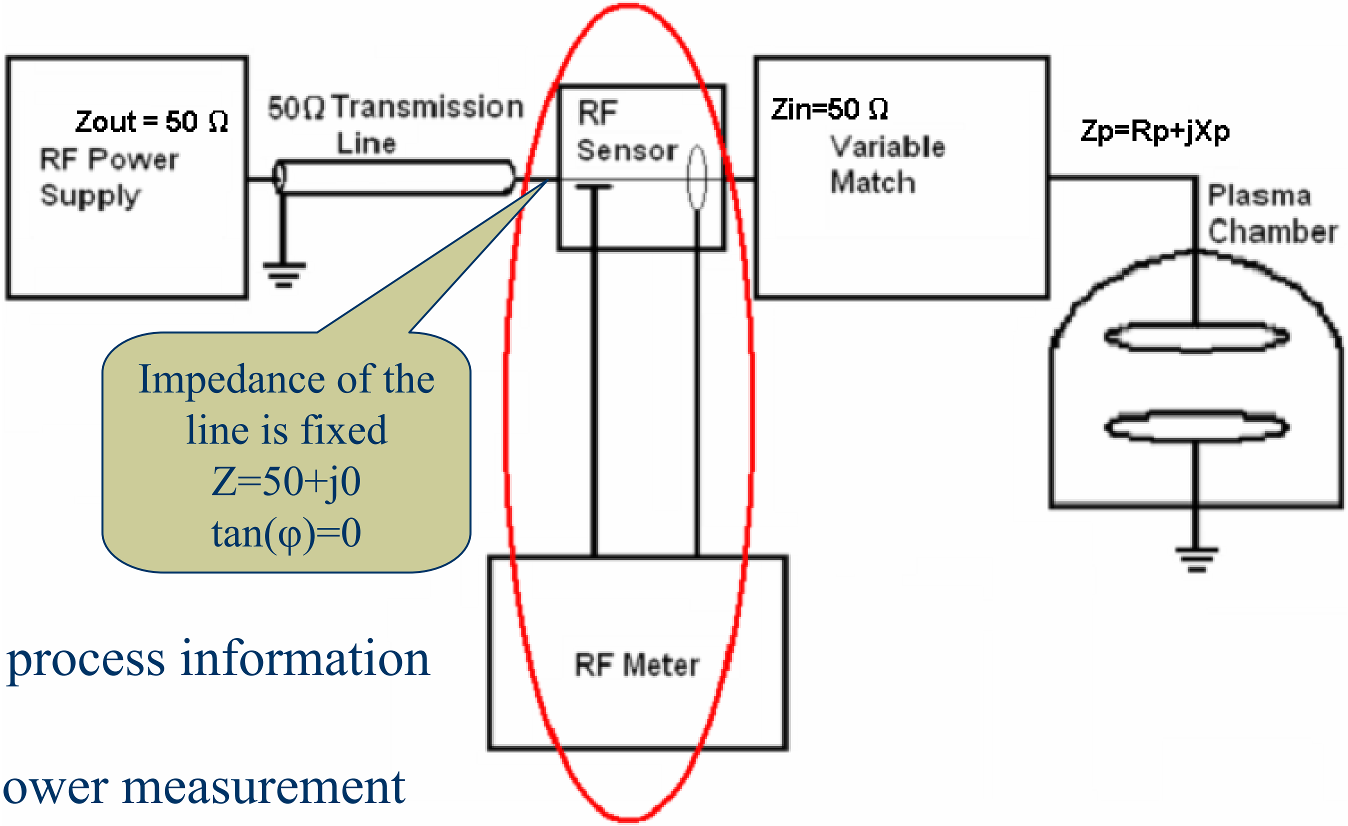
Why is RF High Power Measurement is Important?

- Semiconductor and flat panel industry requires RF Power level up to 50kW with better then 1% power accuracy, for frequencies 1-200MHz
    - Process control
    - Repeatability
    - Faster diagnostics
    - Increased yield
    - Reduced development time
- Existing RF power methods are typically 1-3% accurate into real impedance (50 Ohms)
    - Accuracy is decreasing with VSWR
- We lack a national (e.g. NIST) or international RF high power standard
    - RF high power calibration is performed using only indirect methods

RF High Power Measurement- Topics

- Background on RF High Power Measurement
- New Solutions for Real Impedance Lines and Loads
  - Double diode detector with digital correction
  - Multiplier with digital correction
- New Solutions for Complex Impedance Lines and Loads
  - Direct digital sampling
- Calibration Methods
- Summary and Future work

Real Impedance RF High Power Measurement Application



Impedance of the line is fixed
$Z=50+j0$
$\tan(\varphi)=0$

Advantages:

- Cost effective

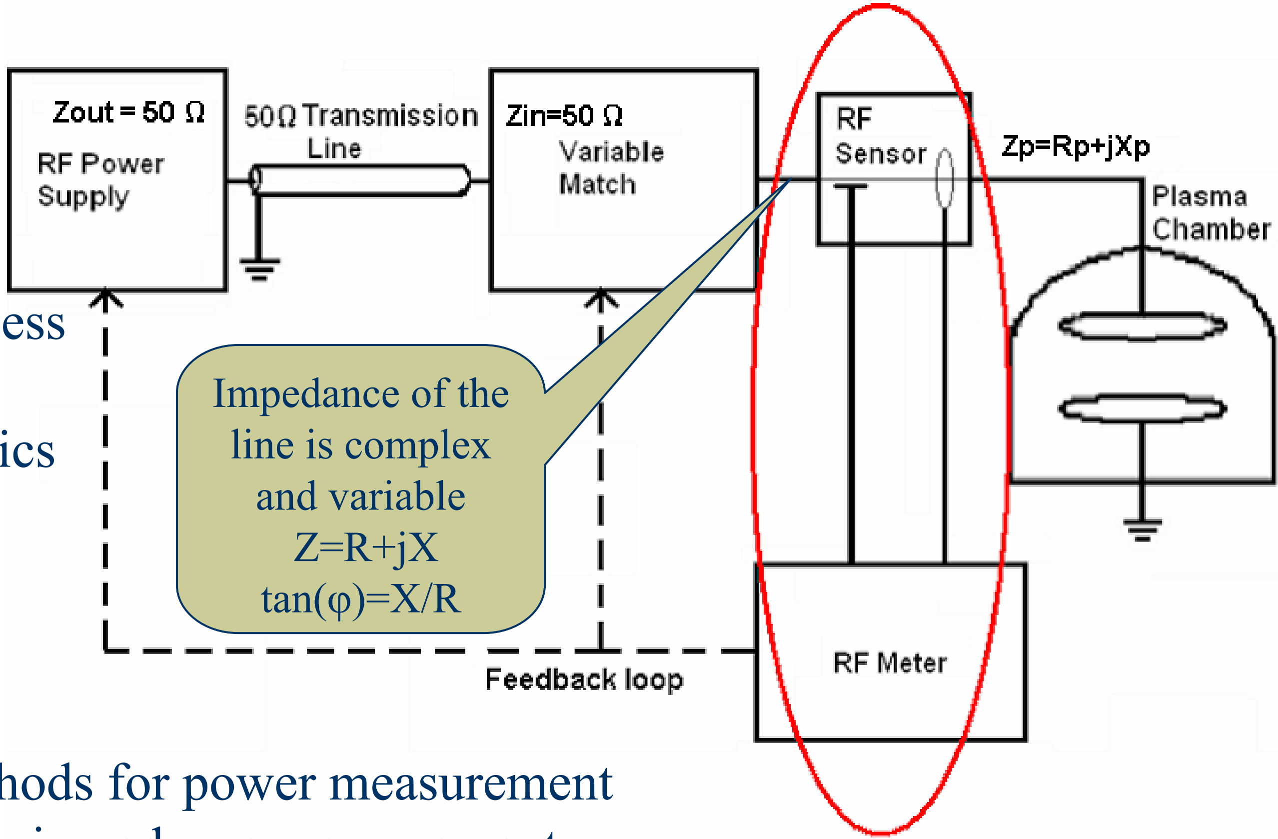
Disadvantages:

- Limited plasma process information

Error of existing power measurement methods is 1%-3%

Proposed methods have 3X better accuracy

Complex Impedance RF High Power Measurement Application



Impedance of the line is complex and variable
$Z=R+jX$
$\tan(\varphi)=X/R$

Advantages:

- Better plasma process control
- Feedback diagnostics

Disadvantages:

- Expensive

Error of existing methods for power measurement is >1% and >1.5% for impedance measurements

New method has 3X better accuracy for power and impedance

High Power RF Power Measurement - Origin of Errors

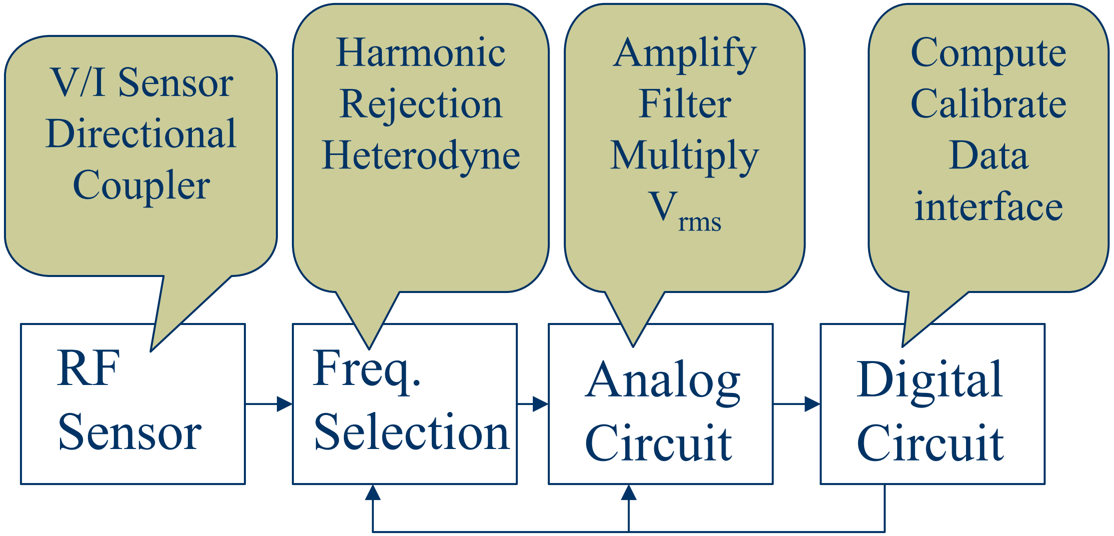
There are 4 categories of errors in RF power measurement:

- RF level linearity (Power/Impedance vs. RF Signal Level)
- Frequency error (Power/Impedance vs. Frequency)
- VSWR error (Power/Impedance vs. VSWR)
- Environmental Stability (Accuracy vs. Humidity and Temperature)

All above errors compound into the total error of the RF measurement method

The RF components have parasitic characteristics and stability issues, therefore any accurate RF measurement requires either "ideal components" or a proper correction (analog and/or digital)

Anatomy of the typical RF High Power Measurement



Advantages:

- Mature technology

Disadvantages:

- Less Accurate. Accuracy is best into 50Ohm and is degrading with VSWR
  - Power Error >1%
  - Impedance Error >1.5%
- Complex
- Accuracy is changing with temperature and humidity

Typical RF High Power Instrument is analog while the new technique is digital …

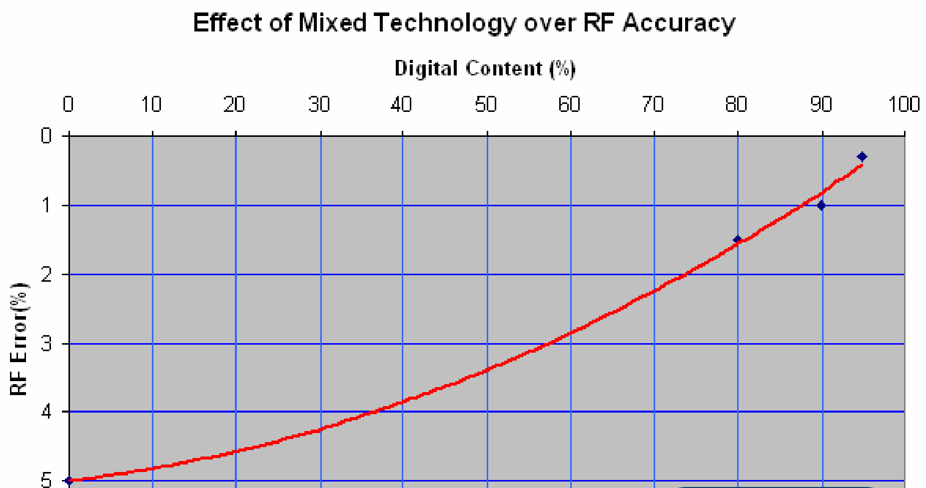
Proposed Enhanced Digital RF Measurement Method

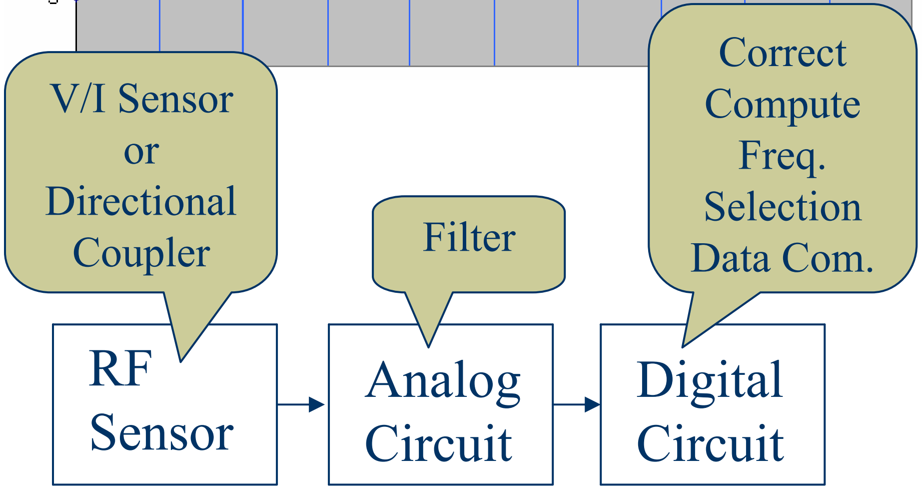
Advantages:

- Better Accuracy
  - Power Error ≈0.3%
  - Impedance Error ≈0.3%
- Smaller size (≈50%)
- Extra features
  - Frequency agile (2-64Mhz)
  - Plasma process feedback
- Environmentally stable

Disadvantages:

- Cost of Development




V/I Sensor or Directional Coupler

Filter

Correct Compute Freq. Selection Data Com.

RF Sensor

Analog Circuit

Digital Circuit

RF Measurement Method for Real Impedances – Background

$P_{load} = V*I*\cos(\varphi)$

For Real Impedance Loads and Lines $\cos(\varphi)=1$ therefore Power Measurement is simplified to V_{rms} measurement:

$$P_{load} = V_{rms}^{2}/Z_0$$

or I_{rms} measurement:

$$P_{load} = Z_0 I_{rms}^{2}$$

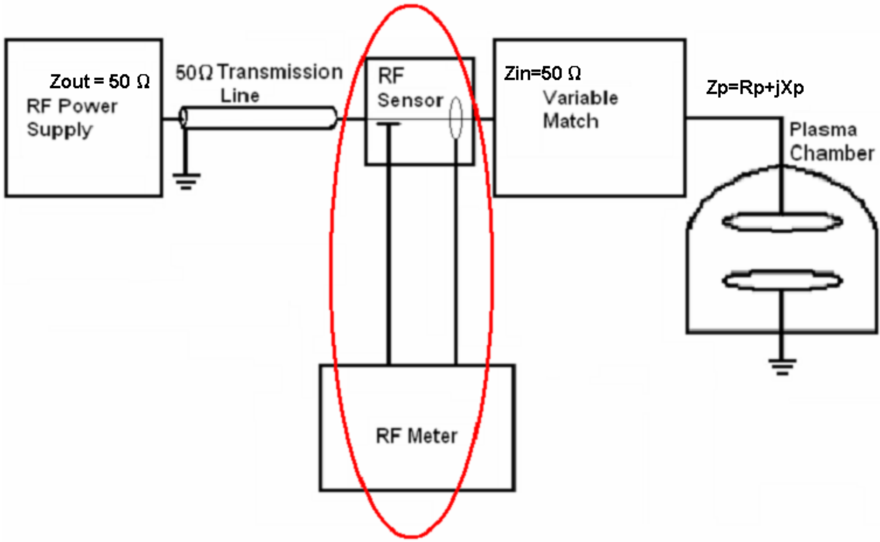
However, on RF we use Forward and Reflected Power as follows:

$P_{load} = P_{fwd} - P_{rfl}$

with the following equations:

$P_{fwd} = V_{fwd}^{2}/Z_0$

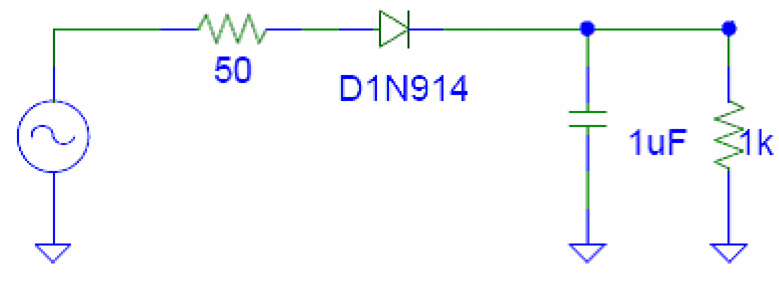
$P_{rfl} = V_{rfl}^{2}/Z_0$



Error of existing power measurement methods is 1%-3%

Proposed methods have 3X better accuracy

Illustrative RF Peak Diode Detector Circuit



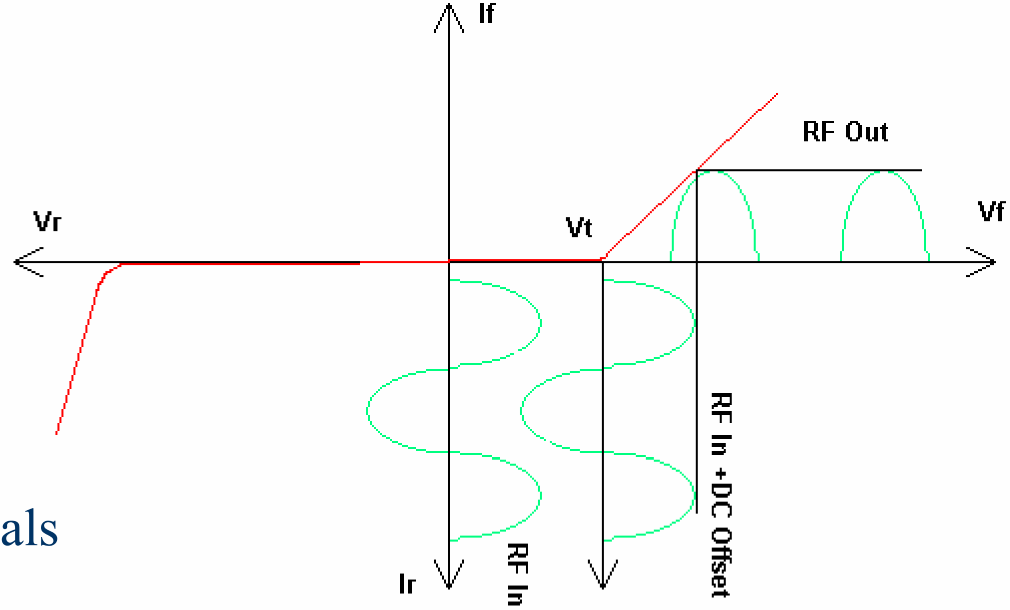
Historically the most basic design for RF voltage measurement

Advantages:

- Simple
- Wide-band

Disadvantages

- Non-linear
- Does not work at low level signals



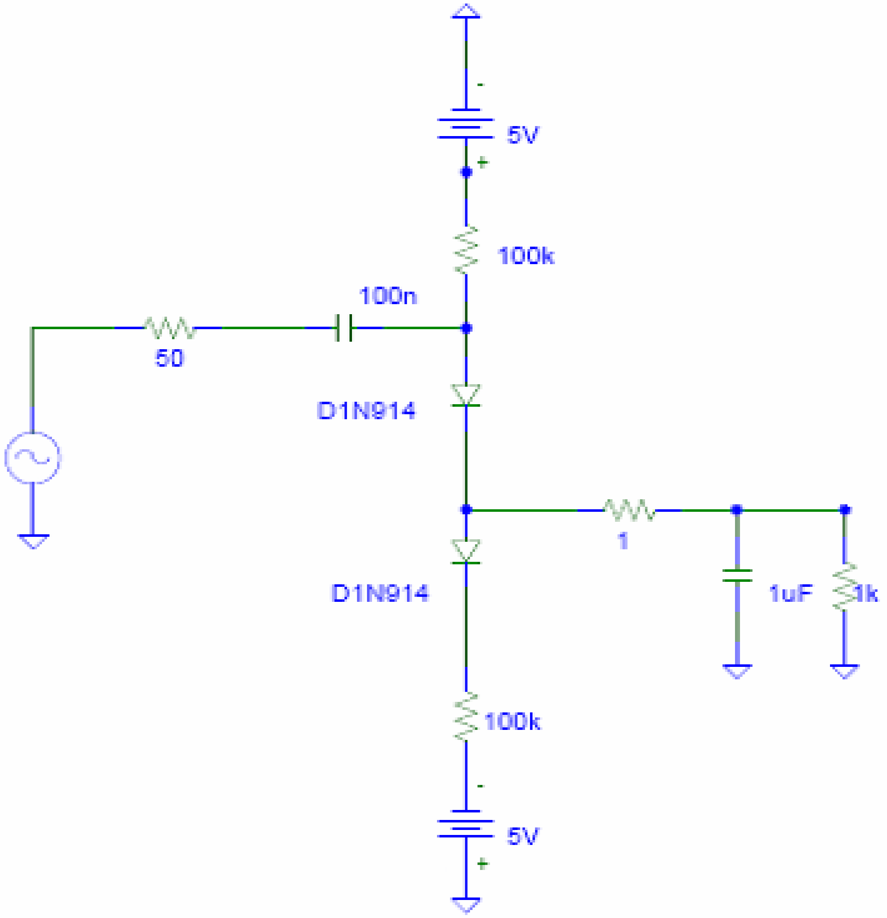
Improved Double Diode Detector Circuit

Advantages:

- Simple
- Wide-band
- Works at low level signals

Disadvantages:

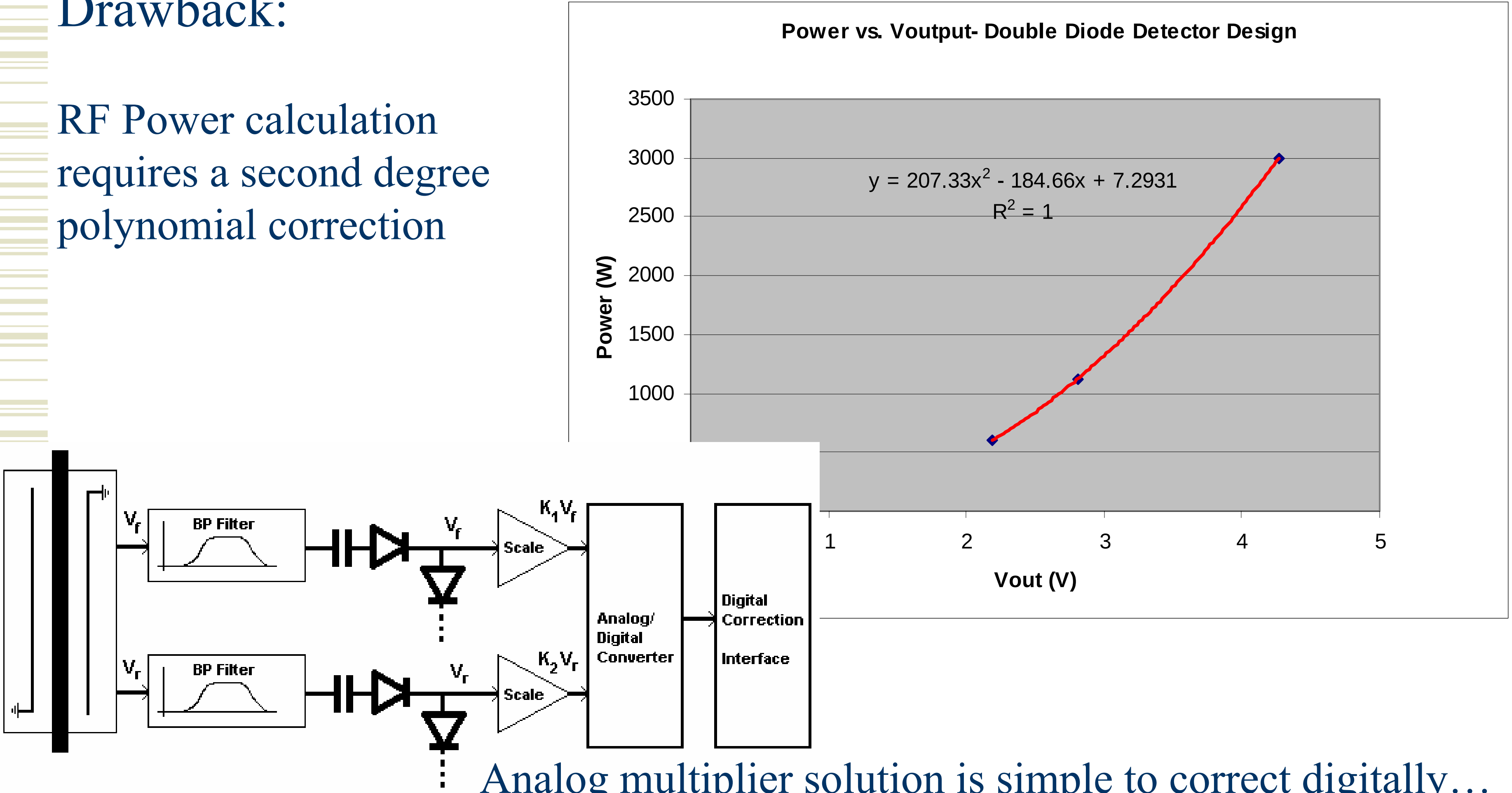
- Non-linear at high signal level



Calculations Required for Calibrating a Double Diode Detector

Drawback:

RF Power calculation requires a second degree polynomial correction



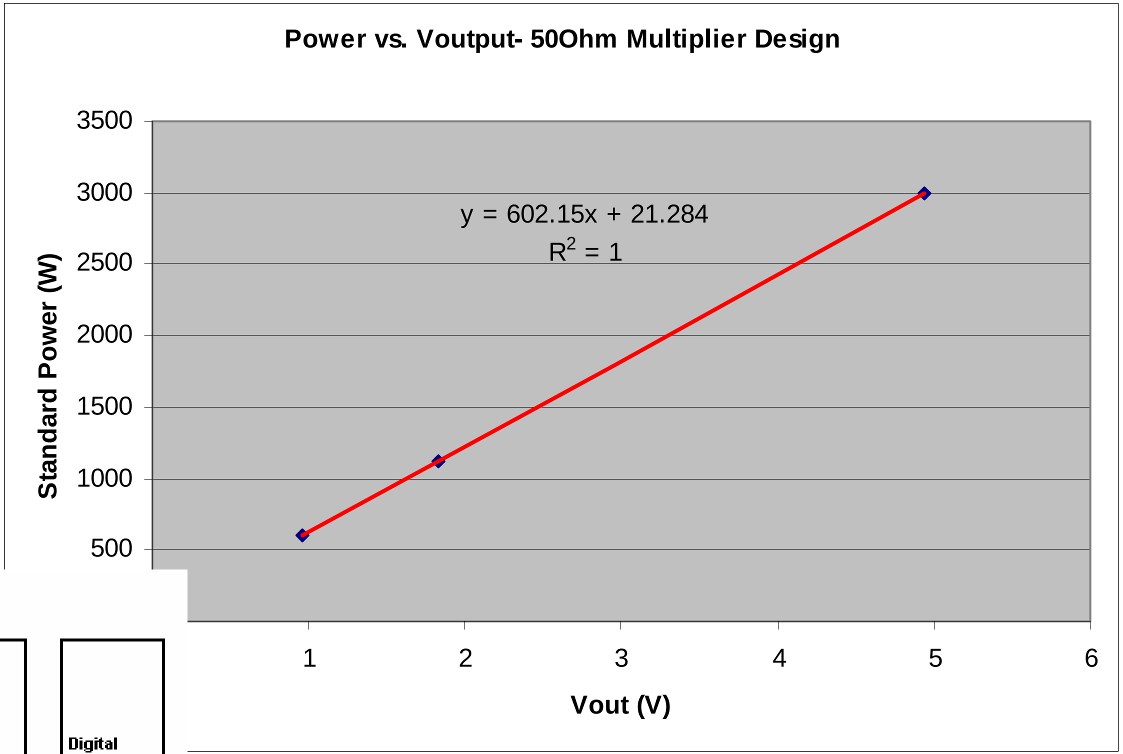
Analog multiplier solution is simple to correct digitally…

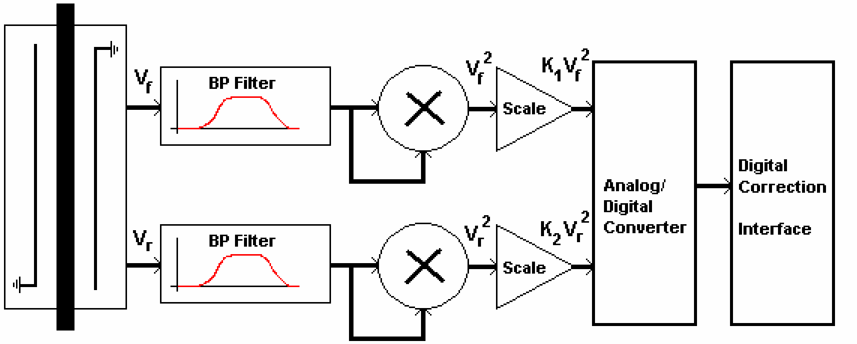
Calculation Required for Multiplier Implementation of Power Measurement

Advantage:

Multiplier will provide the voltage squared

RF Power measurement is linear and requires only scaling and offset correction



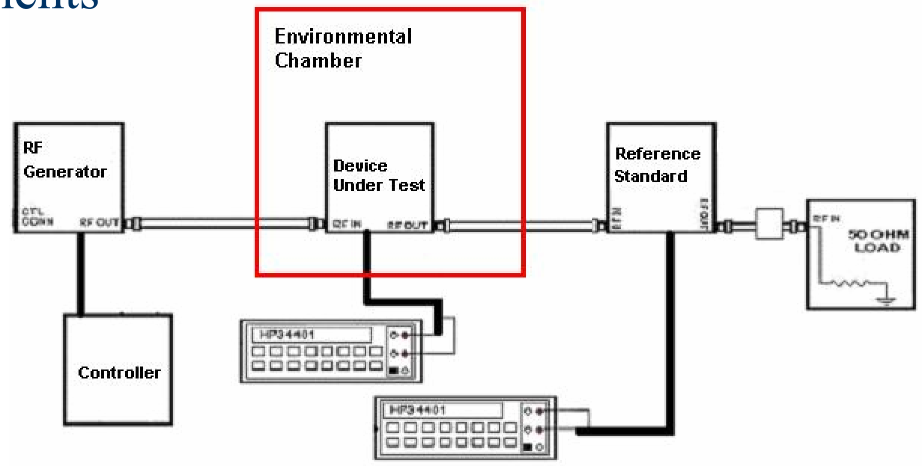


Besides power scaling there are further correction requirements…

P_{RF} Measurements– Other Correction Requirements:Thermal and Bandwidth

Temperature Stability Requirement:

- Tests done in a environmental Chamber confirmed drift of analog components

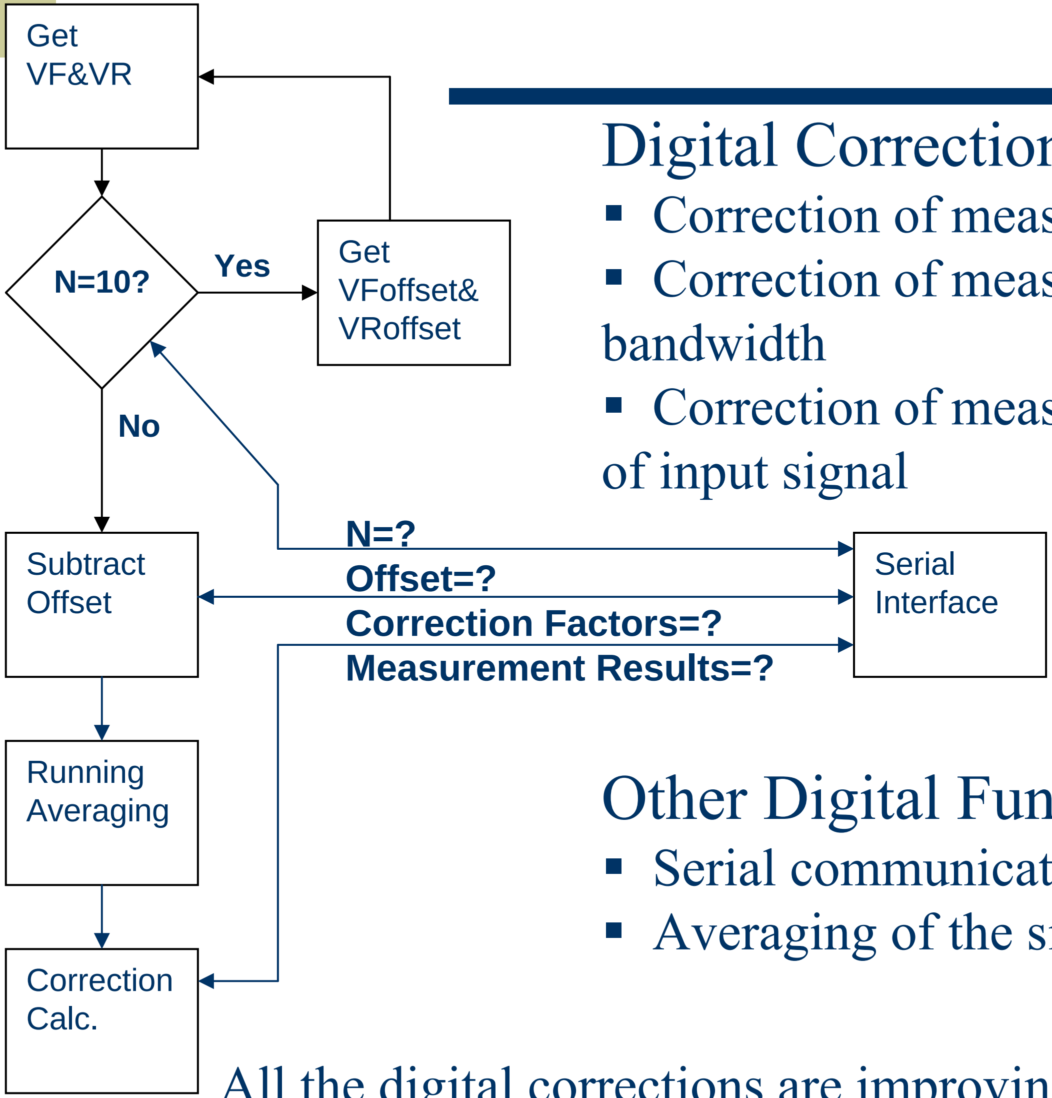


Wideband Requirement:

- For instrumentation with passive input filters a correction of amplitude with frequency is mandatory

Both requirements along with RF Power correction can be solved by DSP…

Illustrative Digital Correction



Get VF&VR

N=10?

Yes

Get VFoffset& VRoffset

No

Subtract Offset

Running Averaging

Correction Calc.

N=?

Offset=?

Correction Factors=?

Measurement Results=?

Serial Interface

Digital Correction will enable:

- Correction of measurement with temperature
- Correction of measurement with frequency bandwidth
- Correction of measurement with amplitude of input signal

Other Digital Functions:

- Serial communications
- Averaging of the signal

All the digital corrections are improving the RF Power accuracy …

Experimental Error Analysis for Multiplier and Double Diode Detector

Standard (W)	Vout (V)	Offset (V)	Slope (W/V)
600	0.962	0.030	644.21
1122	1.828	0.030	624.46
2995	4.94	0.030	610.19

Analog Multiplier results

RF Power equation:

$$x = A/D\_reading$$

$$P = Offset + x * Slope$$

Offset= 21.284W
Slope = 602.15 W/V

Max Error=0.05%

Standard (W)	Vout(V)	Offset (V)	Slope (W/V)
600	2.194	0.781	300.59
1122	2.807	0.781	273.47
2995	4.268	0.781	246.38

Double Diode Rectifier results

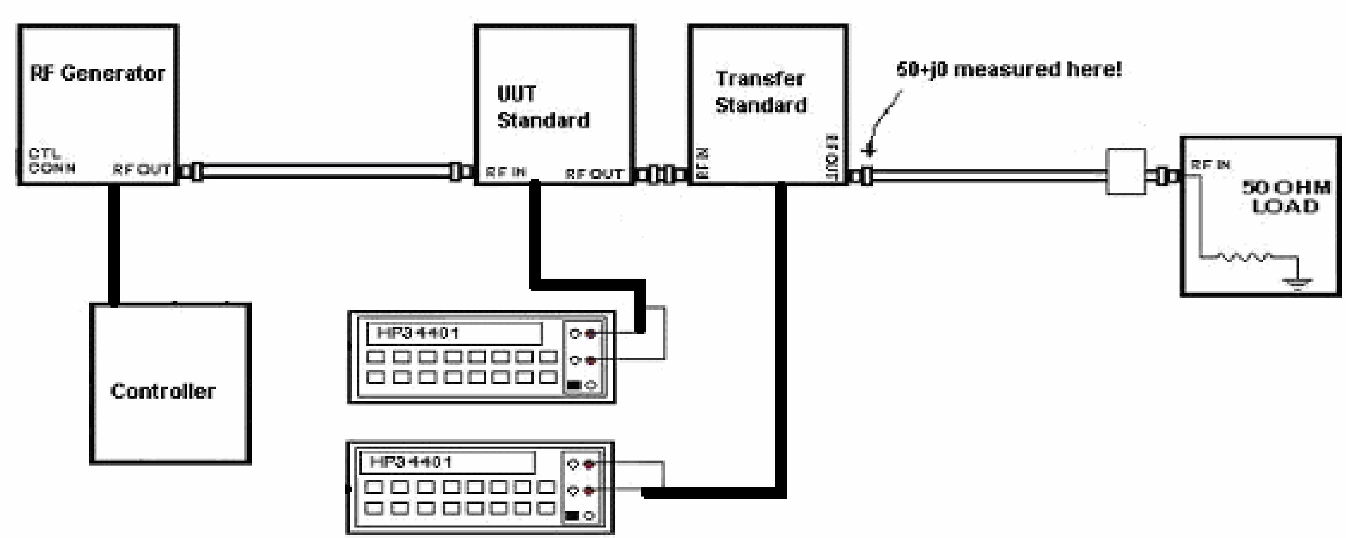
RF Power equation:

$$P = A * x^2 + B * x + Offset$$

Offset= 7.293W
A= 207.33
B=-184.66

Max Error=0.22%

Accuracy Results for the Analog Multiplier with Digital Correction



Calibration results over six devices that employed a multiplier with a digital correction delivered:

- RF Power Error < 0.20% for 30-3000W signal level
- RF Power Error < 0.30% within 15°C-45°C

Results were compared to a Reference Standard calibrated on a calorimeter

In conclusion …

Conclusions for Real Impedance Measurement Methods

Two improved methods were developed for RF high power measurement

1) Double diode detector technique with digital correction
2) Multiplier technique with digital correction

Both designs employ a digital correction for frequency bandwidth and temperature variations

Both designs achieved a power error < 0.3% versus the existing state of the art that has a typical error 1-3%

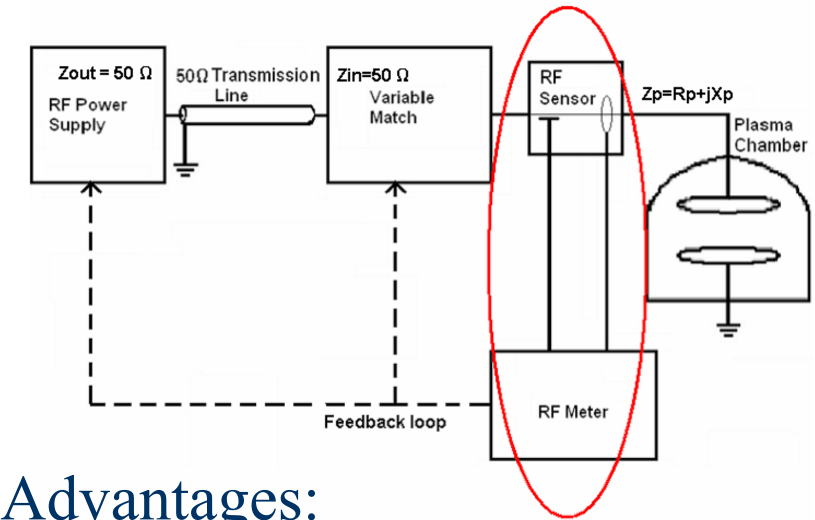
Far more challenging are RF measurements into complex impedances …

RF Measurement for Complex Impedances – Basics

$P_{load} = V*I*\cos(\varphi)$

For measurements into complex impedance loads and lines the most difficult element to measure (and major source of errors) is:

$\cos(\varphi)$



Advantages:

- Better plasma process control
- Feedback diagnostics

Disadvantages:

- Expensive

New Method for Measuring Complex Impedances

Advantages:

- Better Accuracy
  - Power Error ≈0.3%
  - Impedance Error ≈0.3%
- Smaller size (≈50%)
- Extra features
  - Frequency agile (2-64Mhz)
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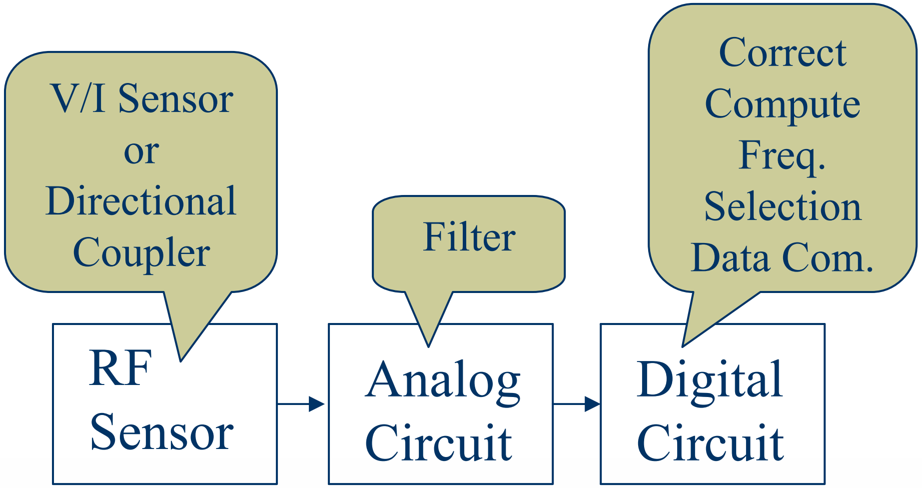
- Environmentally stable



V/I Sensor
or
Directional
Coupler

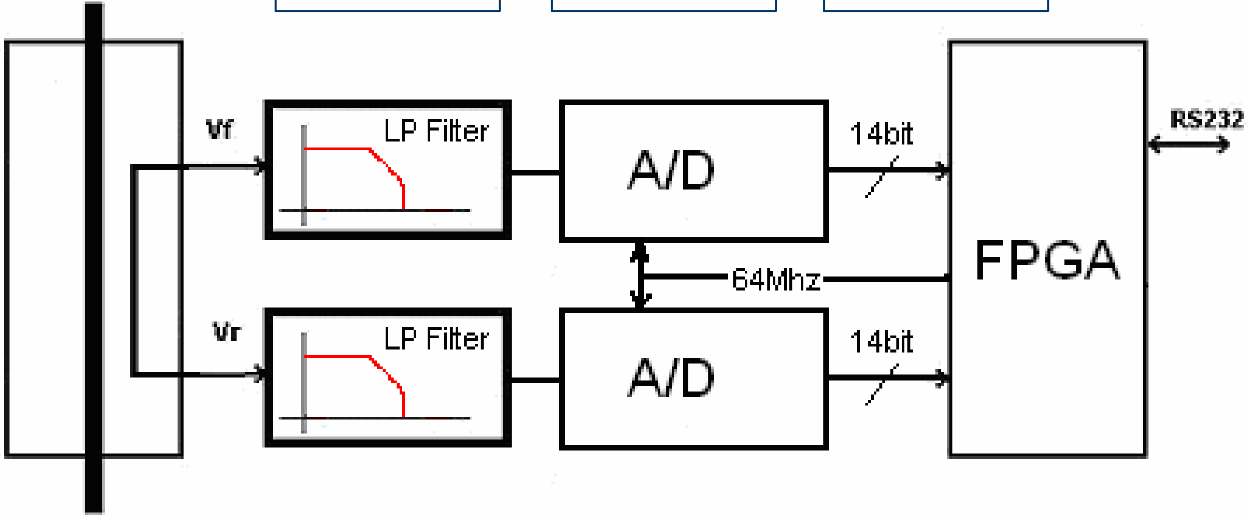
Filter

Correct
Compute
Freq.
Selection
Data Com.

RF Sensor

Analog Circuit

Digital Circuit



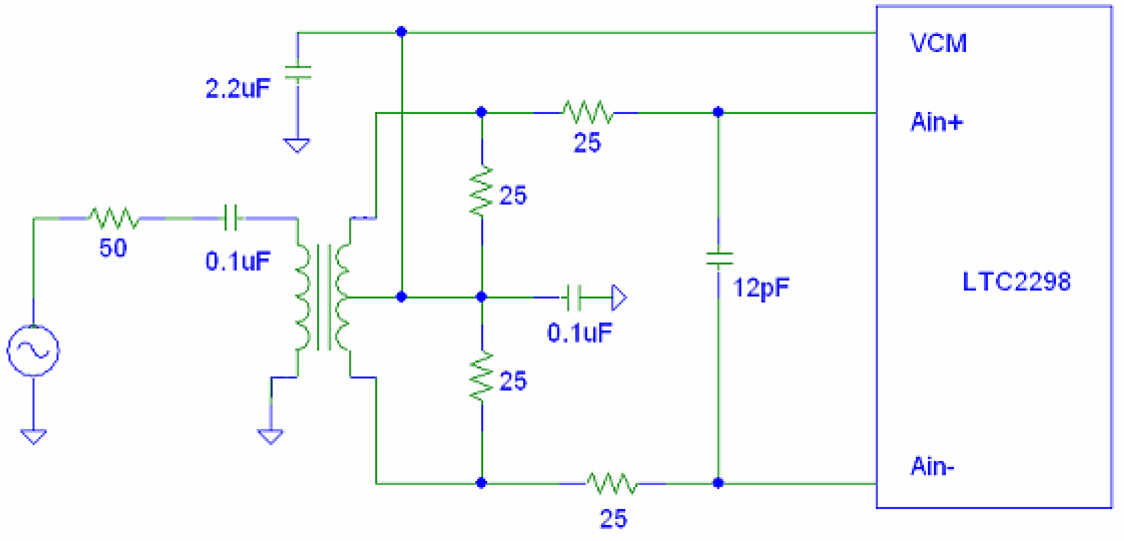
Disadvantages:

- Cost of development

New Method for Measuring Complex Impedances– Direct Digital Sampling

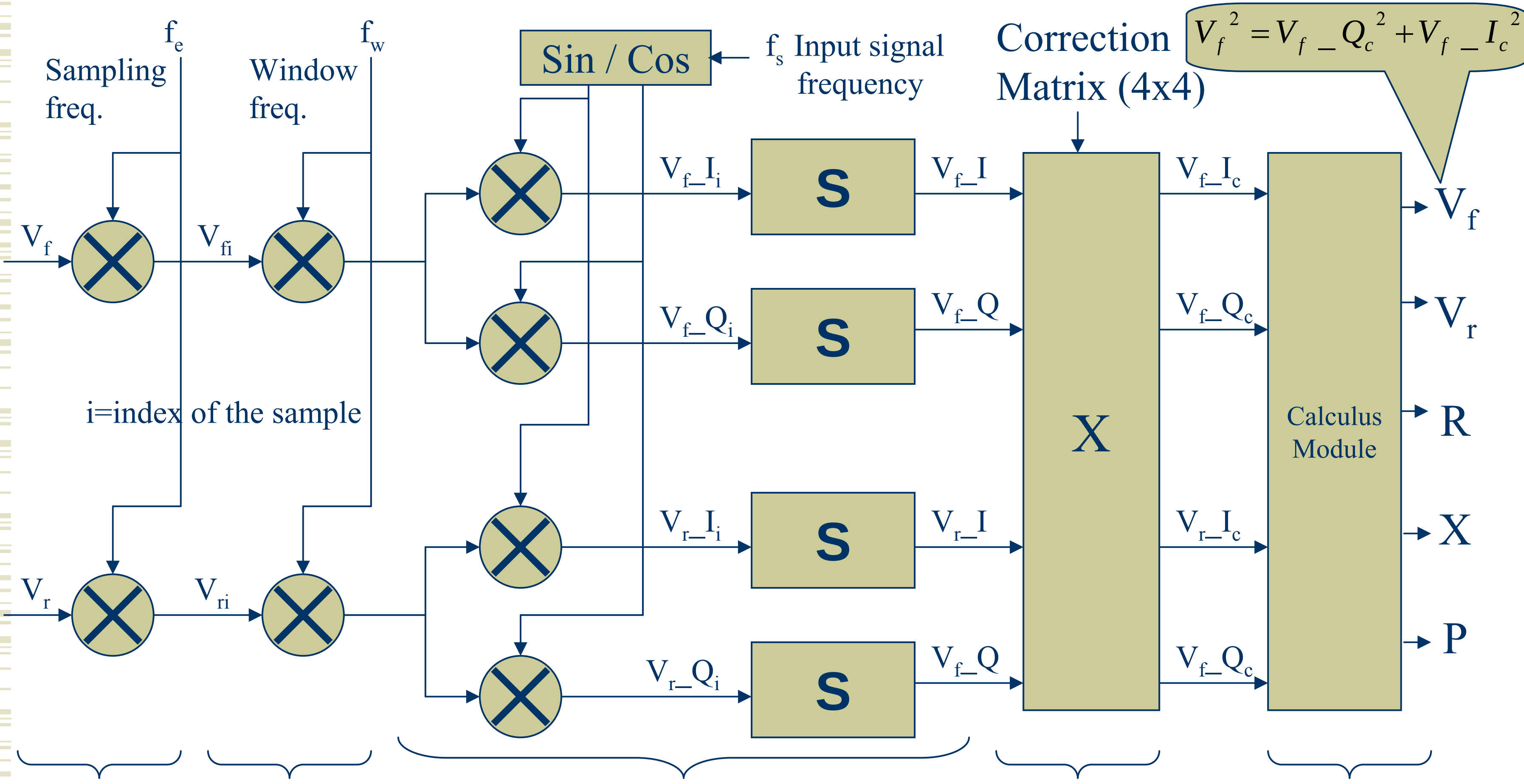
Analog circuit topology consists of:

- Balun Transformer
- Low pass filter



Forward and reflected channels are similar and **parallel sampled**

Direct Digital Sampling Digital Signal Processing Schematic



$$V_f^{\,2} = V_{f\_}Q_c^{\,2} + V_{f\_}I_c^{\,2}$$

Sampling
Hann Window
Fourier Transform
Calibration
RF Calculus

Direct Digital Sampling
Amplitude and Phase Processing I

We know the frequency f_s

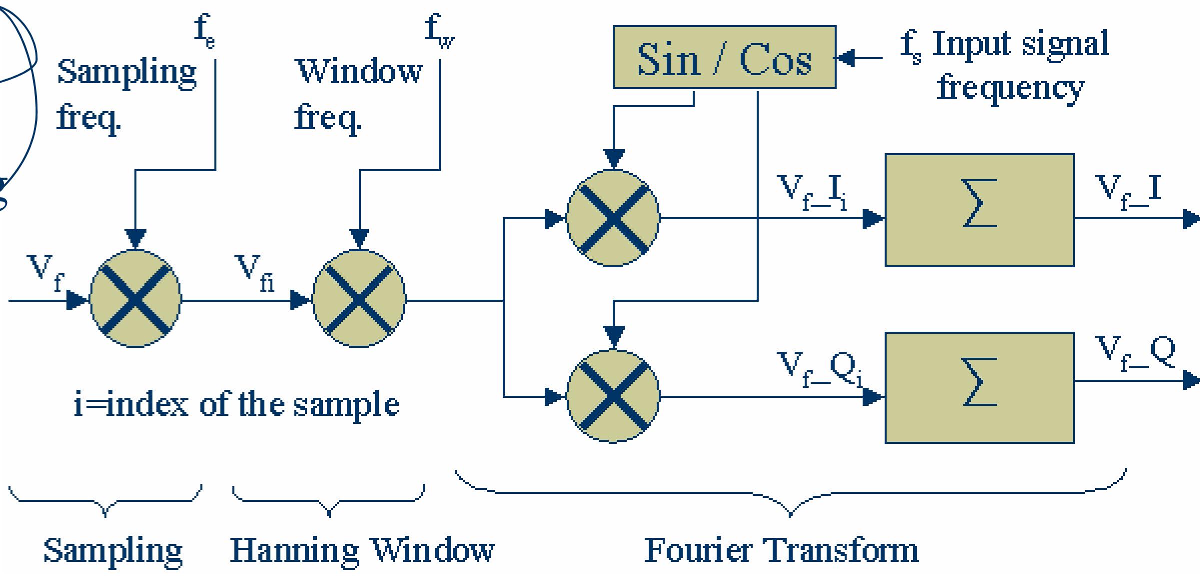
$$V_f = A\sin(\omega_S t + \varphi_f)$$

Digital Sampling

$$V_{fi} = A\sin(\omega_S t_i + \varphi_f)$$

$*\sin(\omega_s t_i)$

$*\cos(\omega_s t_i)$



f_e Sampling freq.

f_w Window freq.

Sin / Cos

f_s Input signal frequency

V_f

V_{fi}

$V_f\_I_i$

$V_f\_Q_i$

Σ

V_f_I

V_f_Q

i=index of the sample

Sampling

Hanning Window

Fourier Transform

$$\begin{cases} V_f\_I_i = A\sin(\omega_S t_i + \varphi_f) * \sin\omega_S t_i \\ V_f\_Q_i = A\sin(\omega_S t_i + \varphi_f) * \cos\omega_S t_i \end{cases} \xleftrightarrow[\text{transform}]{\text{Trigonometric}} \begin{cases} V_f\_I_i = 0.5A[\cos\varphi_f - \cos(2\omega_S t_i + \varphi_f)] \\ V_f\_Q_i = 0.5A[\sin\varphi_f + \sin(2\omega_S t_i + \varphi_f)] \end{cases}$$

Both I and Q components are summed over the observation window …

Direct Digital Sampling Amplitude and Phase Processing II

$$\begin{cases} V_f\_I = \dfrac{1}{N}\displaystyle\sum_{i=0}^{N-1} Vf\_I_i \\ V_f\_Q = \dfrac{1}{N}\displaystyle\sum_{i=0}^{N-1} Vf\_Q_i \end{cases}$$

$$\begin{cases} V_f\_I_i = 0.5A[\cos\varphi_f - \cos(2\omega_S t_i + \varphi_f)] \\ V_f\_Q_i = 0.5A[\sin\varphi_f + \sin(2\omega_S t_i + \varphi_f)] \end{cases}$$

$$\downarrow$$

$$\begin{cases} V_f\_I = \dfrac{A}{2N}\displaystyle\sum_{i=0}^{N-1}\cos\varphi_f + \dfrac{A}{2N}\displaystyle\sum_{i=0}^{N-1}\cos(2\omega_S t_i + \varphi_f) \\ V_f\_Q = \dfrac{A}{2N}\displaystyle\sum_{i=0}^{N-1}\sin\varphi_f + \dfrac{A}{2N}\displaystyle\sum_{i=0}^{N-1}\sin(2\omega_S t_i + \varphi_f) \end{cases} \rightarrow \begin{cases} V_f\_I = \dfrac{A}{2}\cos\varphi_f \\ V_f\_Q = \dfrac{A}{2}\sin\varphi_f \end{cases}$$

After DFT we still have the signal Amplitude and Phase Information

These Sum Terms are Zero because:

a) Observation Period is large compared to the RF signal frequency: $f_w << f_s$

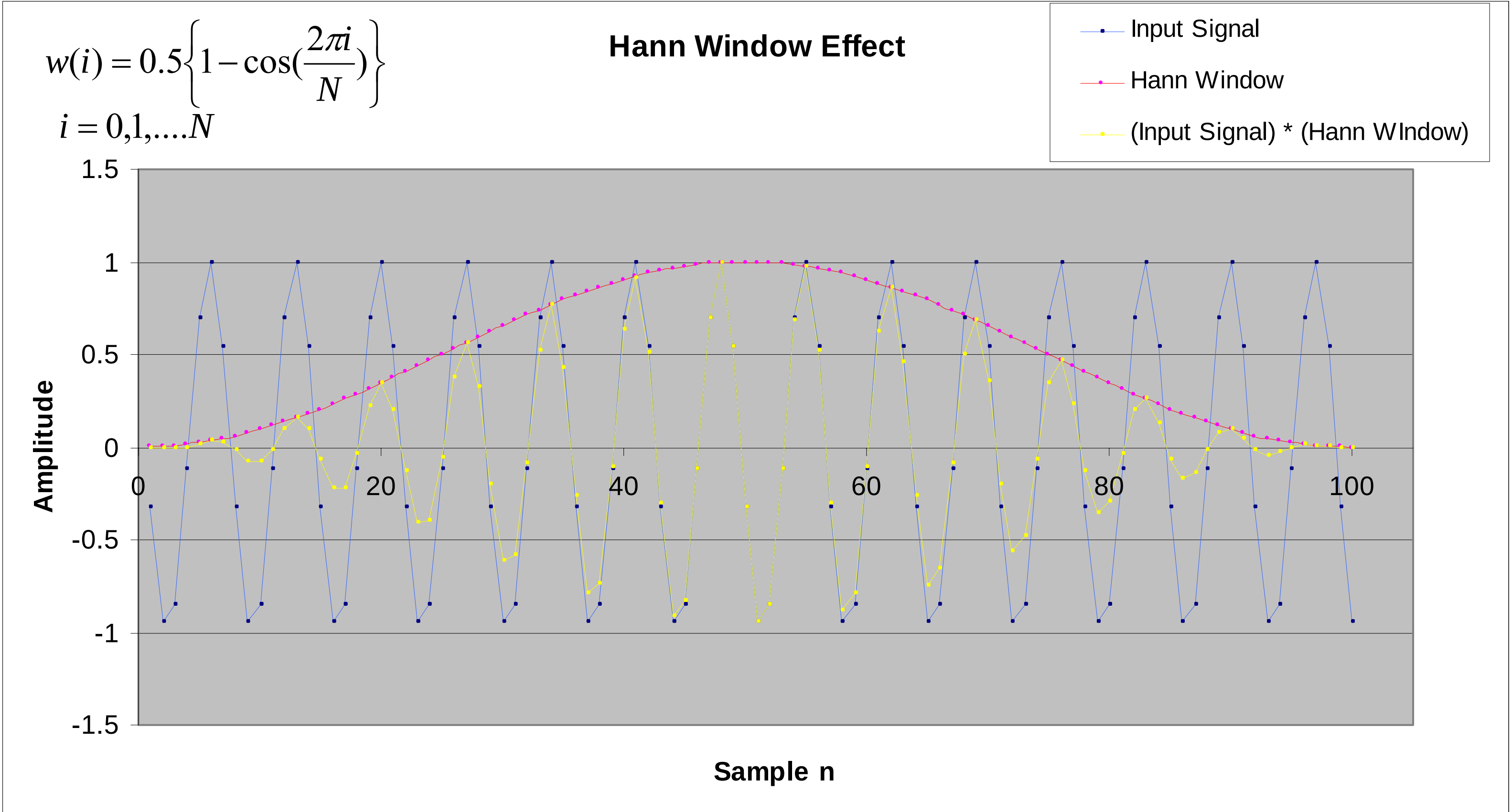
N is the number of samples acquired during the Hann Window

b) Hann function is going to attenuate the beginning and end discontinuities …

Next, both I and Q components are corrected by a calibration matrix …

Hann Window Effect

In this example the Hann window has 1µSec period , the input signal has 13.56MHz and the sampling rate is 100Ms/Sec



$$w(i) = 0.5\left\{1-\cos\left(\frac{2\pi i}{N}\right)\right\}$$

$$i = 0,1,\ldots.N$$

Four Channel Digital Calculation of Correction for Direct Digital Sampling

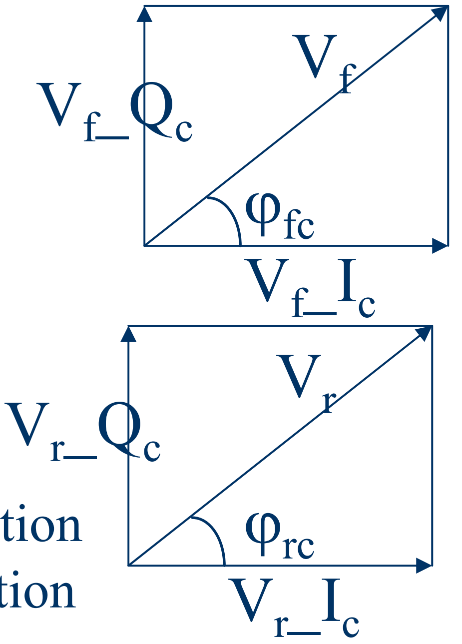
K is a scaling factor for amplitude, does not affect phase

$$\begin{bmatrix} V_{f\_}I_c \\ V_{f\_}Q_c \\ V_{r\_}I_c \\ V_{r\_}Q_c \end{bmatrix} = \boxed{K} * \begin{bmatrix} a11 & a12 & a13 & a14 \\ a21 & a22 & a23 & a24 \\ a31 & a32 & a33 & a34 \\ a41 & a42 & a43 & a44 \end{bmatrix} * \begin{bmatrix} V_{f\_}I \\ V_{f\_}Q \\ V_{r\_}I \\ V_{r\_}Q \end{bmatrix}$$

$$\begin{bmatrix} 1\_0\_0\_0 \\ 0\_1\_0\_0 \\ 0\_0\_1\_0 \\ 0\_0\_0\_1 \end{bmatrix}$$

aij i,j=1 to 4 are calibration factors for phase correction

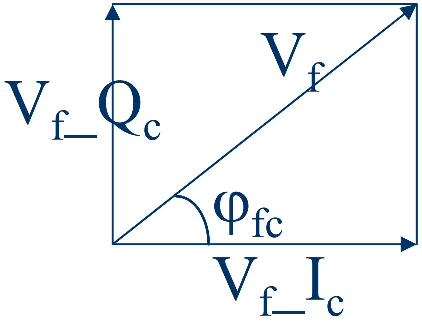
In ideal case (no phase distortion) the correction is the identity matrix



Corrected values for I and Q will provide V_f, V_r and φ…

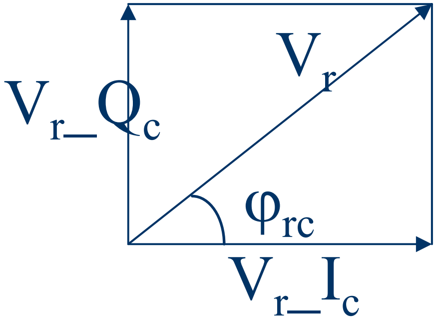
Digitally Corrected Amplitude and Phase for Direct Digital Sampling

The corrected values for I and Q are providing real readings of the input signal



$$V_f{}^2 = V_f\_Q_c{}^2 + V_f\_I_c{}^2$$

$$V_r{}^2 = V_r\_Q_c{}^2 + V_r\_I_c{}^2$$

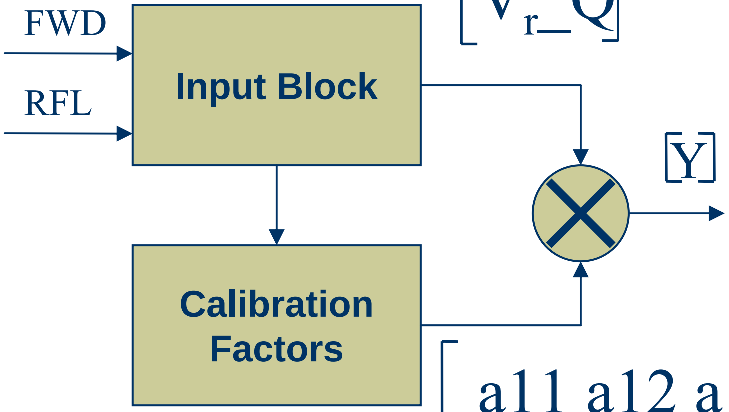


$$\left.\begin{aligned} \varphi_{fc} &= \tan^{-1}\frac{V_{fc}\_Q}{V_{fc}\_I} \\ \varphi_{rc} &= \tan^{-1}\frac{V_{rc}\_Q}{V_{rc}\_I} \end{aligned}\right\} \quad \varphi = \varphi_{fc} - \varphi_{rc}$$

Determination of Calibration Matrix for Complex Impedance Measurements I

$$[X] = \begin{bmatrix} V_{f}\_I \\ V_{f}\_Q \\ V_{r}\_I \\ V_{r}\_Q \end{bmatrix}$$

If we know the **Matrix Y** and the **Matrix X** (as reported by the RF Measurement) in at least 16 cases then we can calculate calibration **Matrix A**



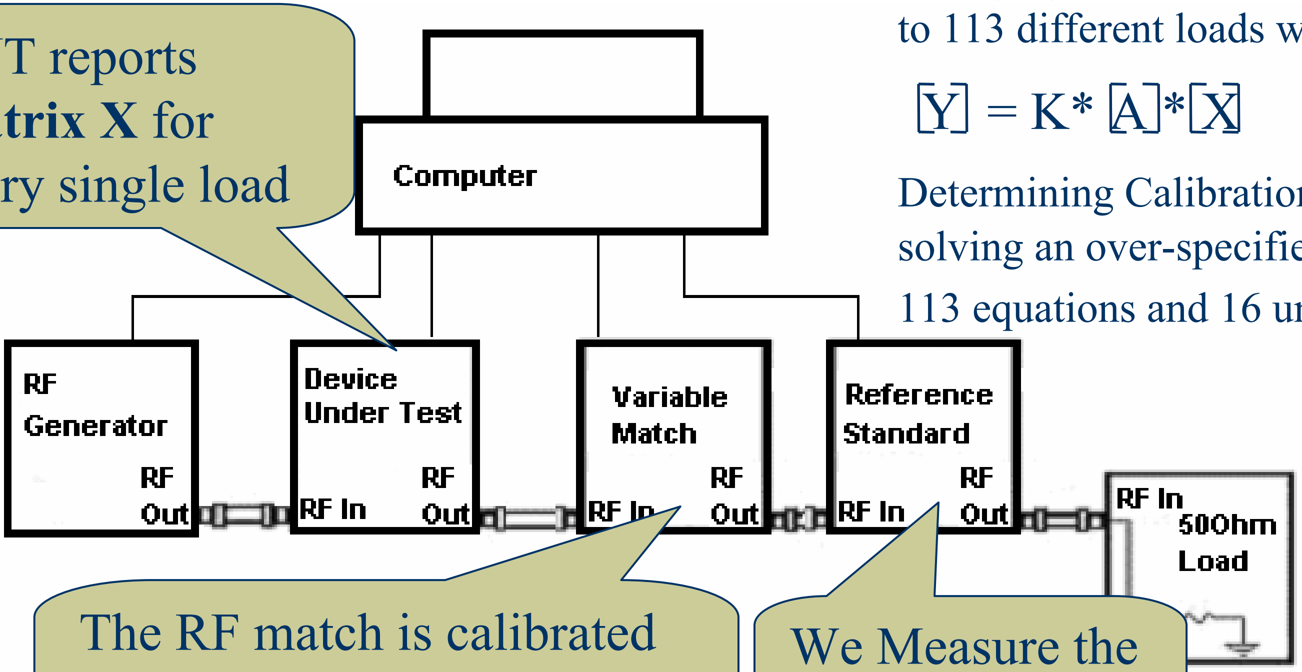
$$[Y] = \begin{bmatrix} V_{f}\_I_{c} \\ V_{f}\_Q_{c} \\ V_{r}\_I_{c} \\ V_{r}\_Q_{c} \end{bmatrix}$$

$$[Y] = K * [A] * [X]$$

$$[A] = K * \begin{bmatrix} a11 & a12 & a13 & a14 \\ a21 & a22 & a23 & a24 \\ a31 & a32 & a33 & a34 \\ a41 & a42 & a43 & a44 \end{bmatrix}$$

How to determine the 16 elements of matrix A ?…

Determination of Calibration Matrix for Complex Impedance Measurements II



DUT reports **Matrix X** for every single load

The RF match is calibrated (known impedance) into 113 loads

We Measure the Power Level

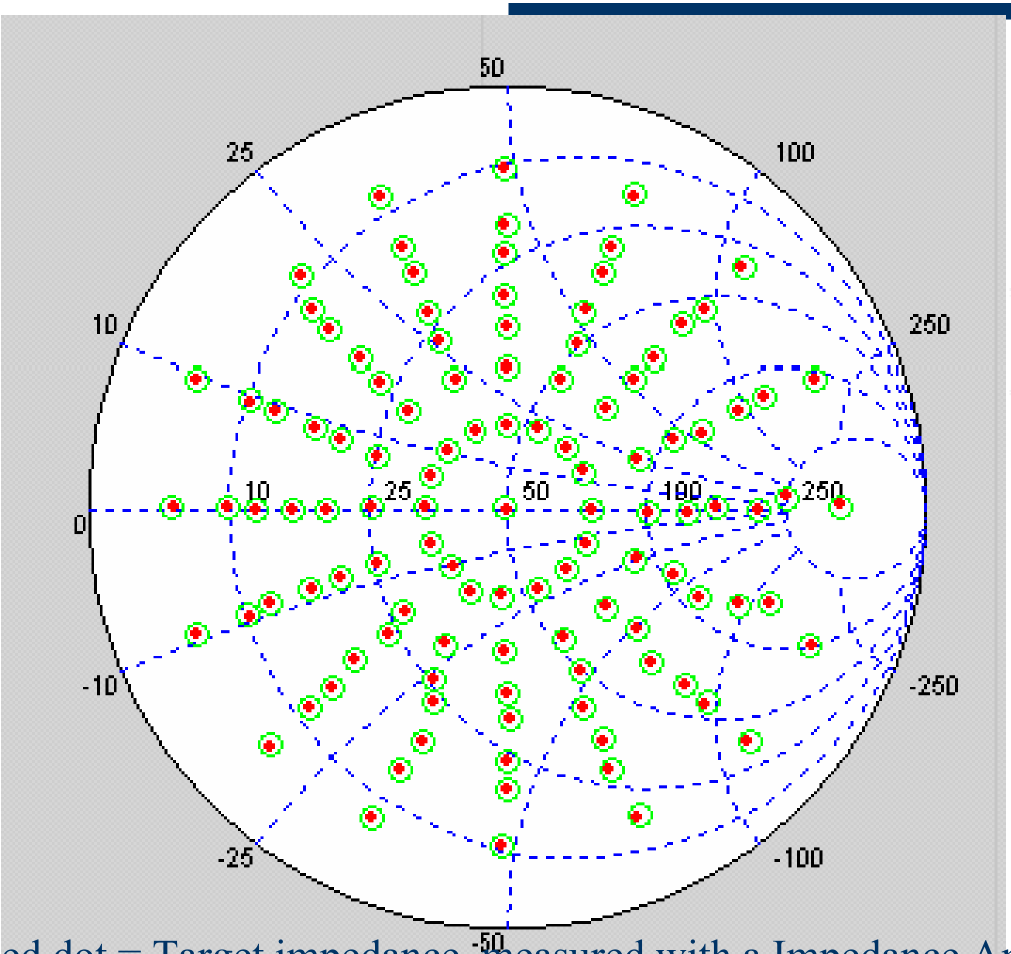
Changing the settings of the Variable Match to 113 different loads will generate 113 equations:

$$[Y] = K * [A] * [X]$$

Determining Calibration **Matrix A** reduces to solving an over-specified system with 113 equations and 16 unknowns

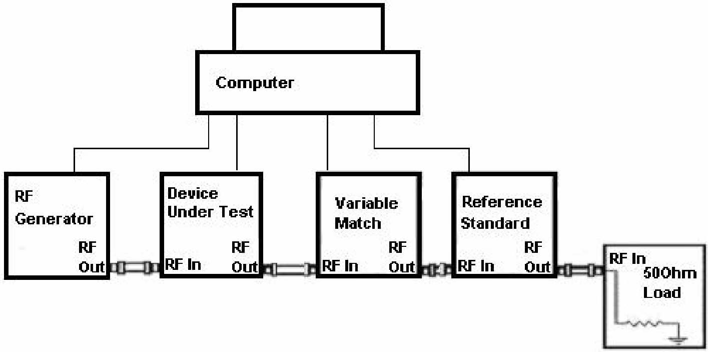
We know the RF signal phase (from the load) and we measure the RF Power, therefore we know **Matrix Y**

Test Results for Direct Digital Sampling into Complex Impedances



Red dot = Target impedance, measured with a Impedance Analyzer
Green Circle = Impedance Measured by the new measurement system

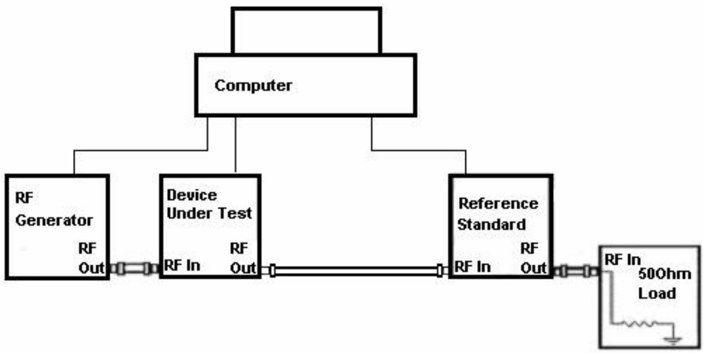
Test bench setup



1) Impedance Error <1% for loads up to VSWR=5

2) 6 different DUT's had an Error<0.1% into a fixed load Z=17+j2.7

Direct Digital Sampling. Power Measurements_Test Results in 50Ω



Power Error < 0.71W compared to a calibrated Reference Standard

Power Error < 0.34%* compared to a calibrated Reference Standard

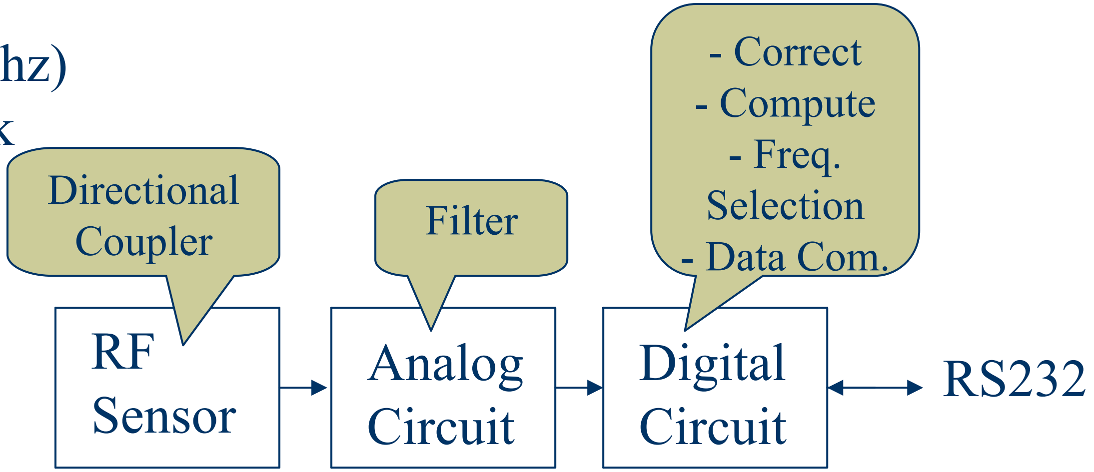
* 0.15% out of the Power Error was identified as systemic calibration issue related to the match losses measurements

RF Power (W)	DUT Power (W)	Reference Standard Power (W)	Error	UM
32	31.37	32.08	-0.71	W
50	49.56	50.07	-0.51	W
100	99.92	99.95	-0.03	W
200	199.67	199.91	-0.24	W
400	399.48	399.88	-0.10	%
800	798.82	800.34	-0.19	%
1000	997.71	1000.98	-0.33	%
1500	1499.47	1501.36	-0.13	%
2000	1999.83	2001.34	-0.08	%
2500	2501.55	2500.45	0.04	%
3000	2984.4	2994.45	-0.34	%

Direct Digital Sampling Conclusions

New RF High Power Measurement Technique with:

- Better Accuracy
  - Power Error ≈0.3% vs. typical 1% of existing methods
  - Impedance Error ≈0.3% vs. typical 1.5% of existing methods
  - Accuracy is consistent over large VSWR
- Smaller size (≈50%)
- Extra features
  - Frequency agile (2-64Mhz)
  - Plasma process feedback
- Environmentally stable



Directional Coupler

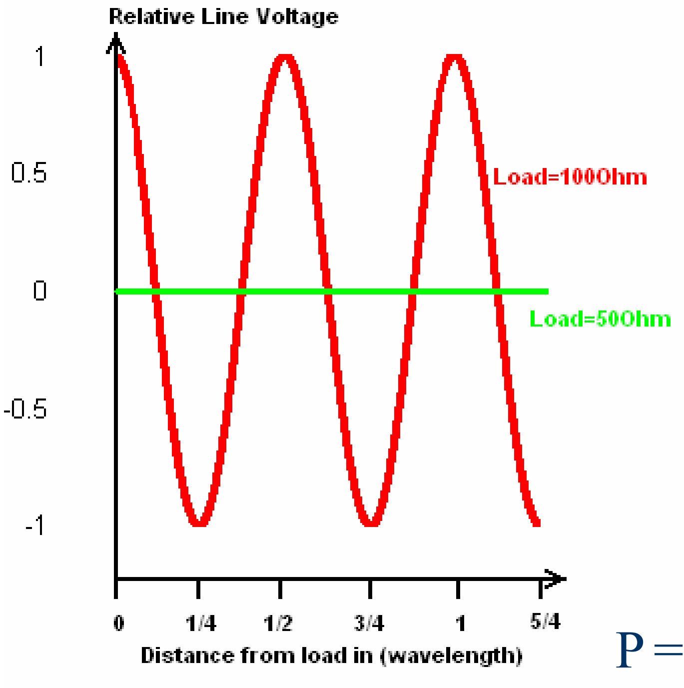
Filter

- Correct
- Compute
- Freq. Selection
- Data Com.

RF Sensor → Analog Circuit → Digital Circuit ↔ RS232

An accurate measurement method should be complemented by a good reference …

Calibration Techniques for High Power RF. Overview



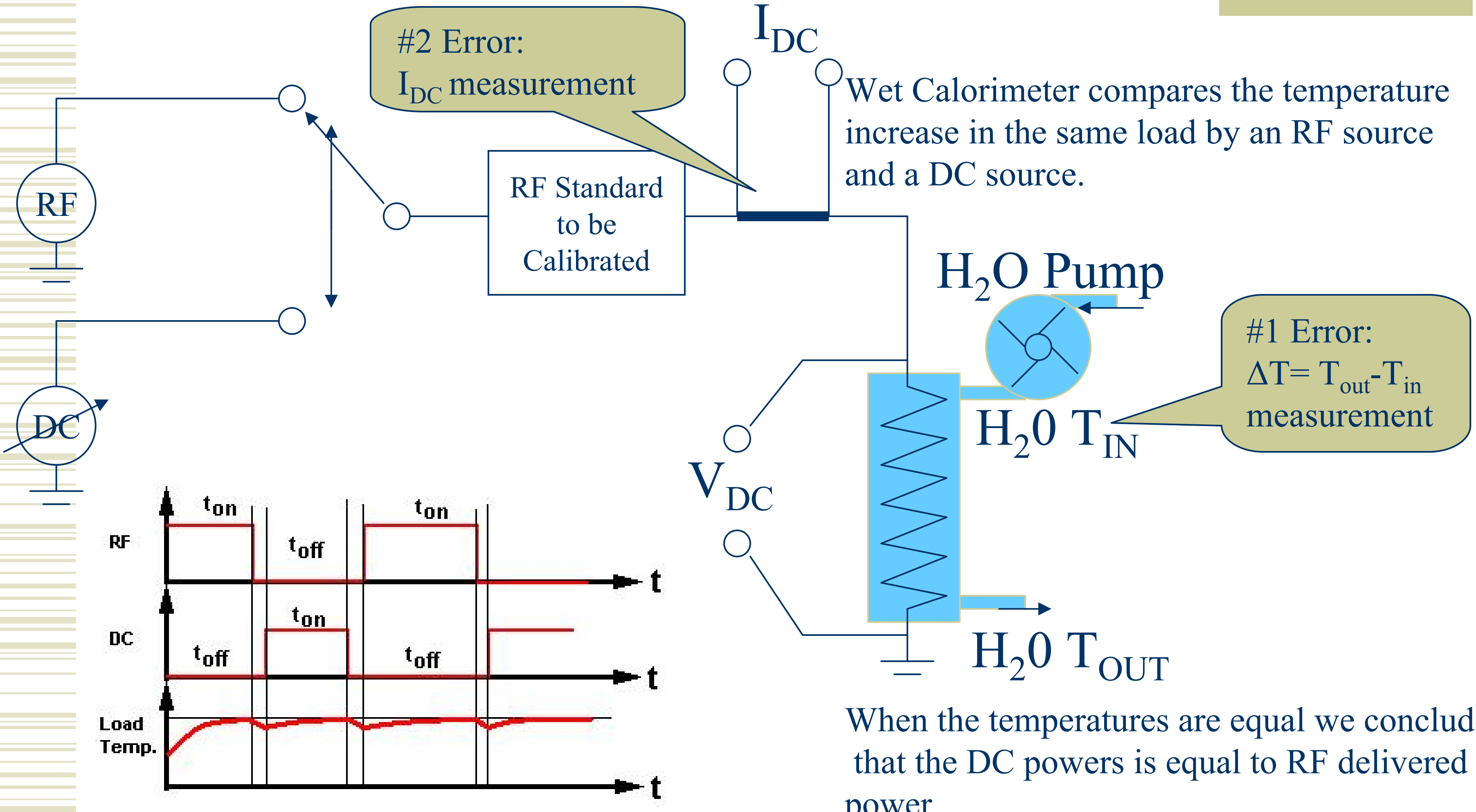
$P = V * I * \cos(\varphi)$

RF Power High Power (>100W) does not have a NIST, nor any other International Standard

There are only Indirect Methods to calibrate RF Power Instruments, typically using substitution methods

In RF, Voltage level is not a good method of Power Measurement

Calibration Techniques for High Power RF. Wet Calorimeter



#2 Error:
I_{DC} measurement

#1 Error:
$\Delta T = T_{out} - T_{in}$ measurement

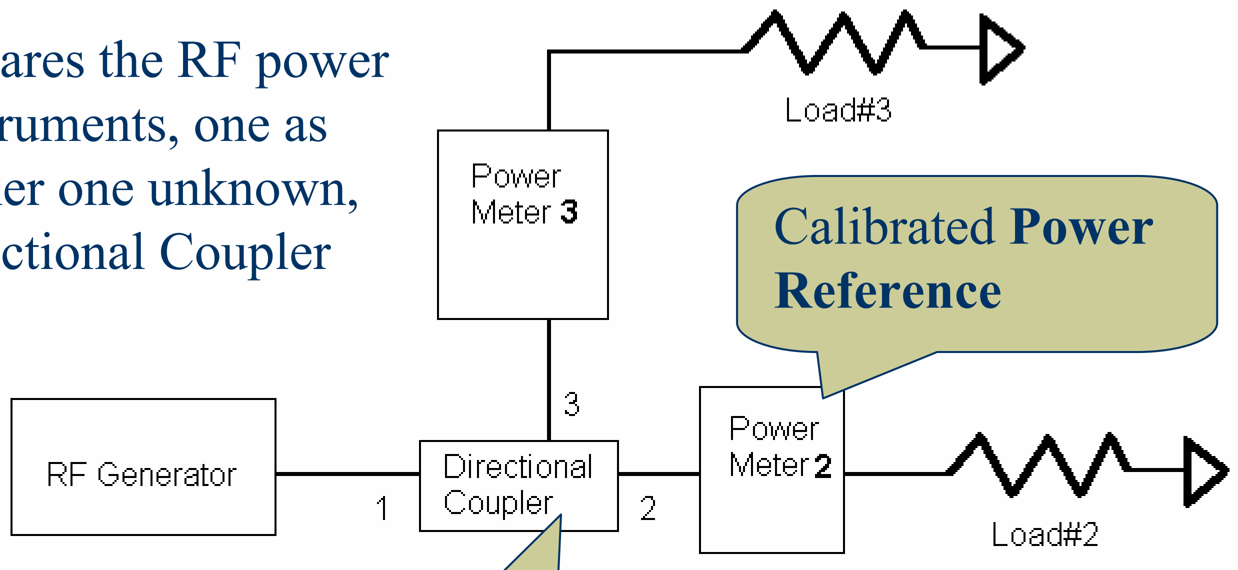
Wet Calorimeter compares the temperature increase in the same load by an RF source and a DC source.

When the temperatures are equal we conclude that the DC powers is equal to RF delivered power

Calibration Techniques for High Power RF. New Technique using Dry Calorimeter I

Dry Calorimeter compares the RF power level between two instruments, one as a reference and the other one unknown, using a calibrated Directional Coupler

$$K = 10 * \log\left(\frac{P_3}{P_2}\right)$$



Calibrated **Power Reference**

A 20dB coupler would have 100:1 Power Ratio (K=100)

Directional Coupler with a calibrated power coupling coefficient, **K**

$$K = \frac{P_2}{P_3}$$

Novel Techniques of RF High Power Measurement. Summary

It is more practical to employ the proper digital correction technique then to research ideal components.

1) Two Improved Techniques of Power Measurement for Real Impedances were presented

- Multiplier followed by digital correction (3X accuracy improvement)
- Double diode detector followed by digital correction

2) A New RF Measurement Technique for Complex Impedances was presented

- Direct digital sampling (3X improvement)
- A new calibration method for complex impedance instruments

Results on all the above methods have lower errors then all previous methods

3) Research results into RF high power calibration methods

- Wet Calorimeter Error Analysis
- New Dry Calorimeter Method

Novel Techniques of RF High Power Measurement. Future Work

It is Impractical to Calibrate all RF Instruments
on the RF Calorimeter; Transfer Standards are employed

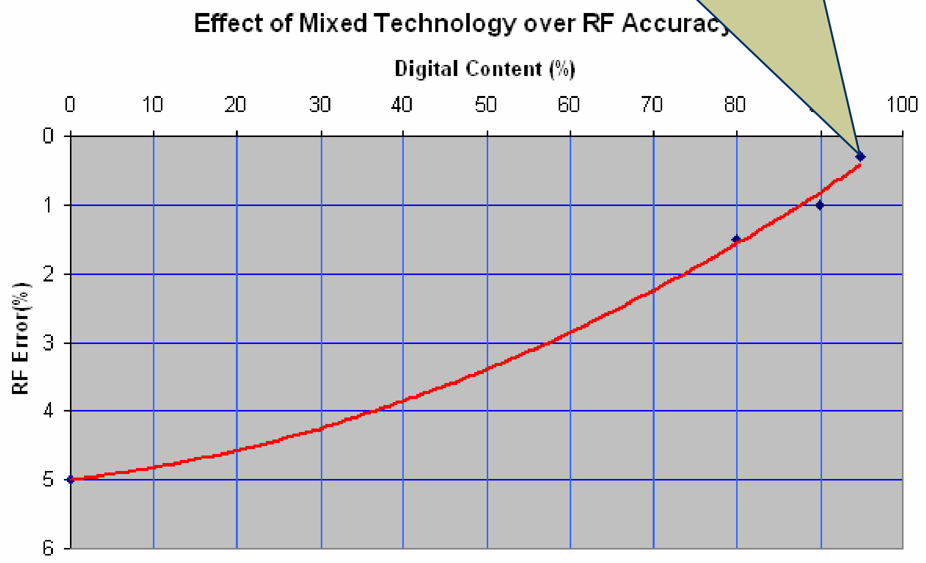
DC Voltage
DC Current
NIST Traceable

RF Calorimeter
DC to RF Cal
Of Transfer
Standard

RF
Instrument
Calibration

RF Calorimeter can improve the absolute accuracy of the measurement

1) Reduce Calibration Time on the RF Calorimeter
by using extrapolation techniques



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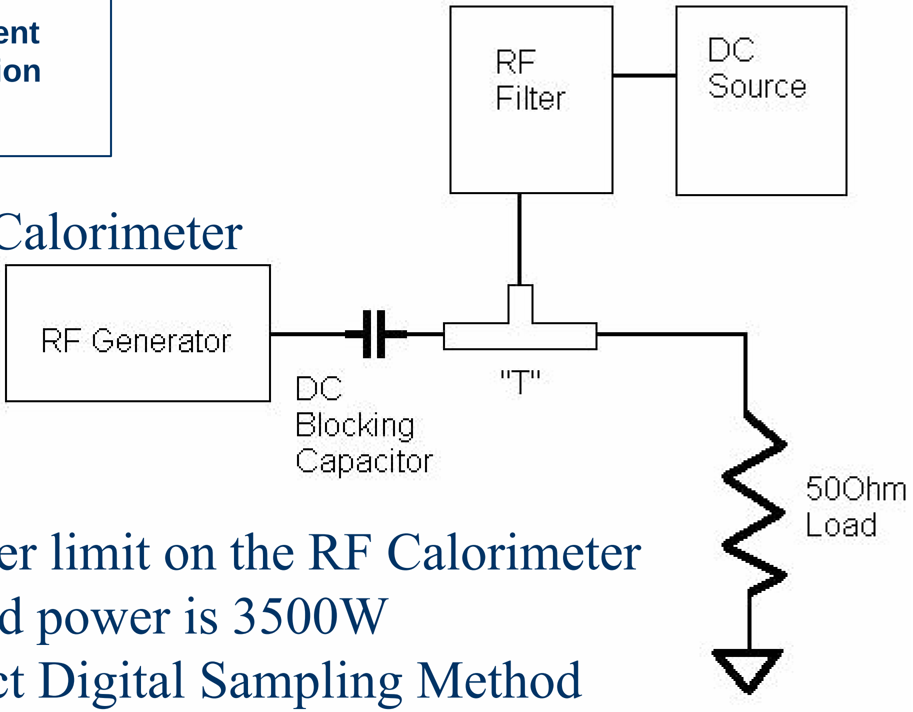

2) Increase reliability and the RF Power limit on the RF Calorimeter
In this moment maximum RF calibrated power is 3500W
3) Research the limitations of the Direct Digital Sampling Method

Novel Techniques of RF High Power Measurement

Questions?