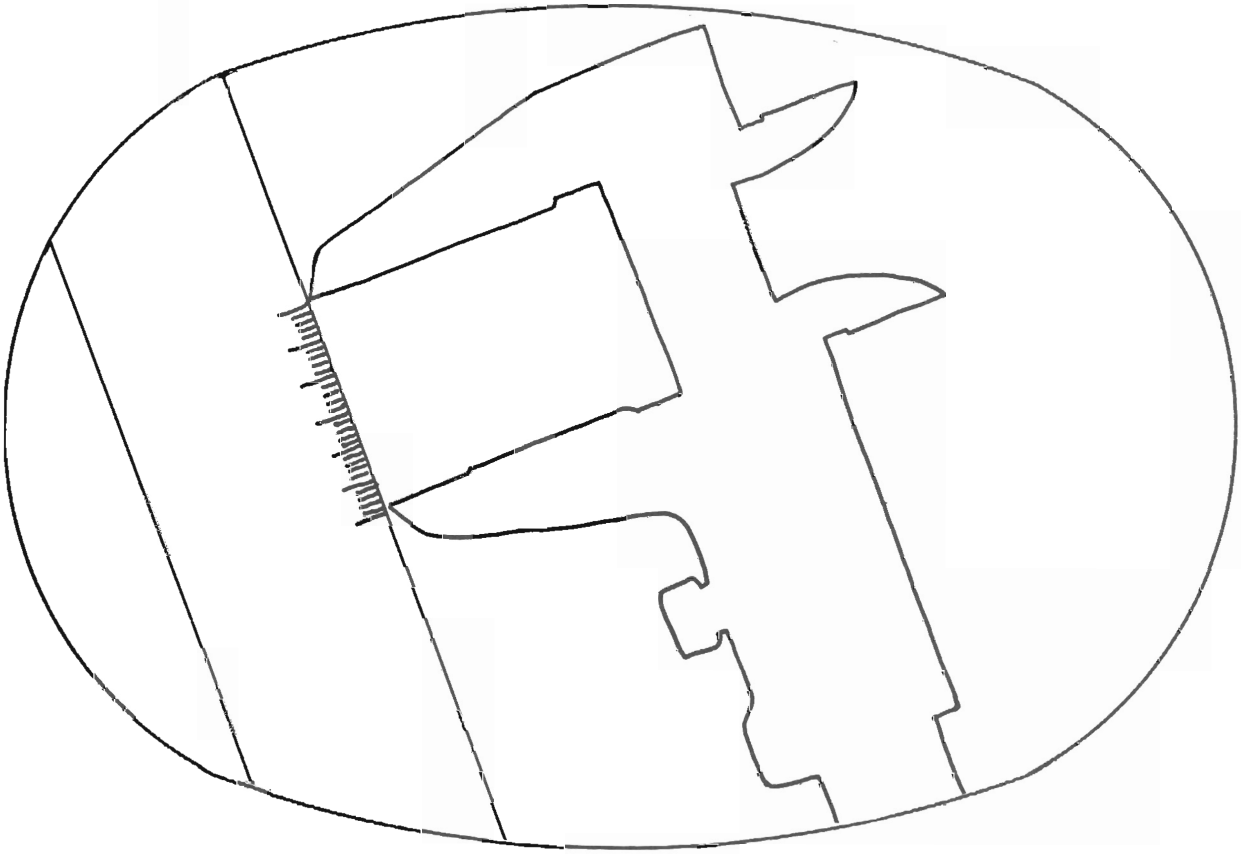
Current status of HP calibration and traceability at mm-wave frequencies



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> Philosophy is intellectual speculation turned into belief. Quantitative agreement of theory with experimental fact distinguishes science from philosophy.
>
> *B.M. Oliver, HP*

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1. Why Traceability & Calibration are Important

Integrity in specifications, and therefore measurements, is necessary for commerciality.

In R&D

- Data can be verified by different engineers and by different entities.
- Experiments can be repeated with consistent results.

In production

- Accurate measurements are needed for quality control.
- Setting specifications and guardbands.
- Determination of yields (pricing).

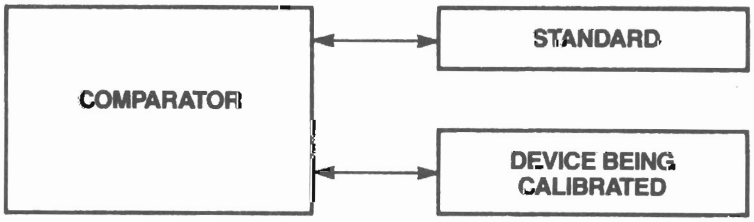
In the market place

- Fair competition based on verifiable performance.
- Discrepancies between buyer and vendor.
- Acceptance of defective products or rejection of good products.

2. Definition Of Terms

Calibration

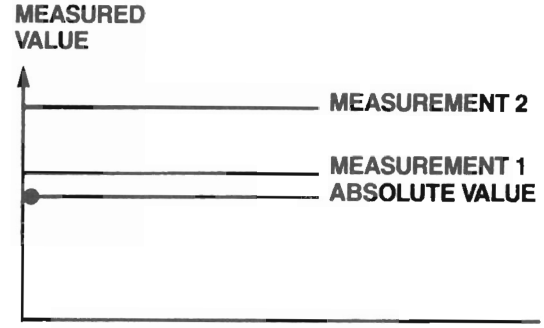
Comparison of a measurement standard or instrument of known accuracy with another standard or instrument to detect, correlate, report, or eliminate by adjustment, any variation in the accuracy of the item being compared (calibrated). In general, a 4 to 1 ratio is needed for calibration.



2. Definition Of Terms

Accuracy

How close a measurement is to the known absolute value of the parameter being measured.

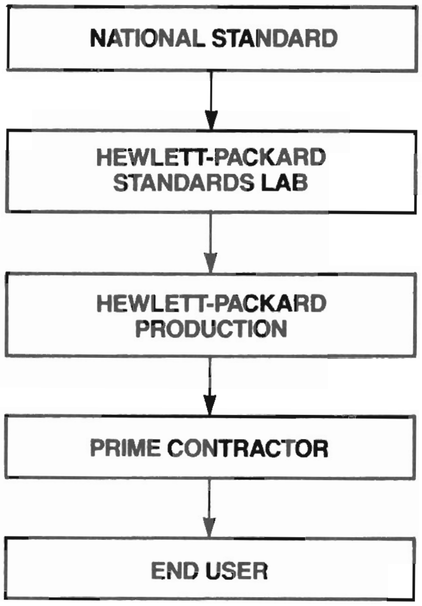


Measurement 1 Is More Accurate Than Measurement 2.

2. Definition Of Terms

Traceability

The ability to relate individual measurement results to national standards or nationally accepted measurement systems through an unbroken chain of comparisons.



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3. Important parameters at mm-wave frequencies

- Impedance
- Attenuation
- Power
- ENR
- Frequency

The performance of these parameters (and therefore their measurement and traceability), is essential to the performance of systems. For example, impedance matching determines transfer of power. Attenuation is used to accurately control power levels. In many cases, power output needs to be known to comply with government regulations. Plus, system output and input power levels determine loss budgets.

4. Effect of flange quality on performance of mm-wave components

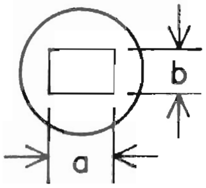
At mm-wave frequencies, flange performance and alignment are critical. They affect. . .

- Reflections
- Directivity
- Radiation
- Repeatability

Because of the increasingly smaller waveguide dimensions at mm-wave frequencies, minute misalignments will have much greater effect in performance than at lower frequencies.

4. Effect of flange quality on performance of mm–wave components

Example of how waveguide and flange misalignment affect performance at Q–band



from MIL–F–3922/67B–006

$a = 0.224$ in, waveguide horizontal dimension

$b = 0.112$ in, waveguide vertical dimension

$\Delta_a = \pm 0.0015$ in, specified max waveguide misalignment in vert. direction

$\Delta_b = \pm 0.0015$ in, specified max waveguide misalignment in horiz. direction

$\Delta_a' = \pm 0.0035$ in, specified max flange misalignment in vert. direction

$\Delta_b' = \pm 0.0035$ in, specified max flange misalignment in horiz. direction

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4. Effect of flange quality on performance of mm–wave components

From IEC–standard publication 154–2, 2nd edition 1980

$$\text{Return loss} = 10 \log_{10} \frac{}{\left[\frac{\lambda_g^2 \Delta_a}{4a^3} + \frac{\Delta_b}{b}\right]^2 + \left[\frac{4.9348 \lambda_g (\Delta a')^2}{a^3} - \frac{7.8957 (\Delta b')^2}{\lambda_g b}\right]^2} \text{ dB}$$

$$\boxed{\text{Return loss} = 31.4 \text{ dB}}$$

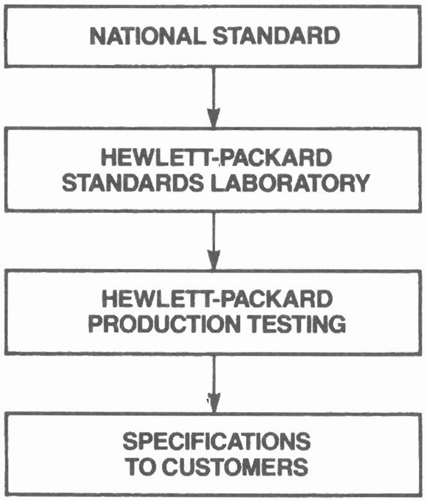
This means that a Q-band coupler that was at the limit of its dimensional specifications when connected to a perfect load would be limited to a directivity of 31.4 dB.

5. Different methods of traceability (or performance verification)

- Traceability to a national standard
- Indirect traceability
- Traceability to standards of other countries

5. Different Methods Of Traceability (Or Performance Verification).

Traceability To A National Standard



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SPECIFICATIONS TO CUSTOMERS

5. Different methods of traceability (or performance verification)

Indirect traceability

- Impedance at μ–wave frequencies through dimensional standards

$$\underset{\text{in coax}}{Z_o} = 59.94 \log_e\left(\frac{D_{outer}}{D_{inner}}\right)$$

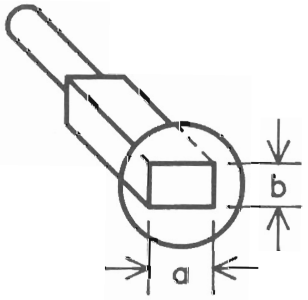
D_{outer} = diameter of outer conductor

D_{inner} = diameter of inner conductor

- Attenuation at μ–wave frequencies through linear frequency conversion. Standard is calibrated at IF frequency.
- Calibration to a known physical parameter. ENR of noise sources through hot and cold loads, referred to temperature.

5. Different methods of traceability (or performance verification)

Example of impedance traceability thru dimensional standards of sliding load



a and b dimensions are measured with a laser interferometer to accuracies of ±0.000020 inch.

5. Different methods of traceability (or performance verification)

Procedure

1. Determine $Z_{\text{wave impedance}}$ using the theoretical value of a

$$Z_{\text{wave impedance}} = 377 \left(1 - \frac{\lambda}{4a^2}\right)^{-1/2}$$

at each frequency of interest.

2. Next, determine the theoretical characteristic impedance $Z_{\text{theoretical}}$ by using the theoretical values of a and b

$$Z_{\text{theoretical}} = \frac{\pi b}{a} Z_{\text{wave impedance}}$$

3. Determine the actual waveguide impedance by measuring a and b

$$Z_{\text{actual}} = \frac{\pi b}{a} Z_{\text{wave impedance}}$$

4. Determine the residual reflection coefficient of sliding load

$$\Gamma_{\text{resd.}} = \frac{Z_{\text{actual}} - Z_{\text{theoretical}}}{Z_{\text{actual}} + Z_{\text{theoretical}}}$$

When a statement of accuracy is made, such as Γ error = 0.006 +0.009 Γ_D, the 0.006 term includes the Γ of the sliding load plus some other system errors.

6. NBS mm–wave calibration capabilities for...

- **Impedance**
- **Attenuation**
- **Power**
- **ENR**

6. NBS mm-wave calibration capabilities
Impedance

	Now		Future (early '86)	
	Measurement Method	Uncertainty	Measurement Method	Uncertainty
K_a-band * WR-28 26.5-40 GHz	Tuned W-G Reflectometer 30 MHz IF	0.001 +0.003 Γ_D	W-G Dual 6-port	Being evaluated
Q-band WR-22 33-50 GHz	–	–	W-G Dual 6-port	Being evaluated
U-band WR-19 40-60 GHz	–	–	Covered by Q & V-band	–
V-band WR-15 50-75 GHz	Tuned W-G Reflectometer	0.001 +0.003 Γ_D	–	–
	W-G Single 6-port	0.001 +0.003 Γ_D		
W-band WR-10 75-110 GHz	W-G Single 6-port	0.001 +0.003 Γ_D	–	–

*HP R-band

6. NBS mm-wave calibration capabilities
Attenuation

	Now		Future	
	Measurement Method	Uncertainty	Measurement Method	Uncertainty
K_a-band WR-28 26.5-40 GHz	Tuned W-G Reflectometer 30 MHz IF	0.5%	–	–
Q-band WR-22 33-50 GHz	–	–	–	–
U-band WR-19 40-60 GHz	–	–	–	–
V-band WR-15 Limited to 55-65 Ghz	Tuned W-G Reflectometer 30 MHz IF	0.5%	–	–
W-band WR-10 75-110 GHz		–	–	–

6. NBS mm–wave calibration capabilities

Power

	Now		Future	
	Measurement Method	Uncertainty	Measurement Method	Uncertainty
K_a–band WR–28 26.5–40 GHz	Microcal	1%	W–G Dual 6–port	Being evaluated
	Tuned W–G Reflectometer	1%		
Q–band WR–22 33–50 GHz	–	–	W–G Dual 6–port	Being evaluated
U–band WR–19 40–60 GHz	–	–	Covered by Q & V–bands	–
V–band WR–15 Limited to 55–65 Ghz	Microcal	2%	–	–
	Tuned W–G Reflectometer	2%		
W–band 75–110 GHz	Microcal	3%	–	–
	W–G Dual 6–port	3%		

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6. NBS mm–wave calibration capabilities

ENR

	Now		Future (early '88)	
	Measurement Method	Uncertainty	Measurement Method	Uncertainty
K_a–band WR–28 26.5–40 GHz	–	–	–	–
Q–band WR–22 33–50 GHz	–	–	Noise sources 40–50 GHz	Being evaluated
U–band WR–19 40–60 GHz	–	–	Covered by Q & V–bands	–
V–band WR–15 Limited to 55–65 Ghz	Total Power Radiometer	+0.15 dB	–	–
W–band WR–10 Limited to 94–95	Automated Radiometer	+0.13 dB	Noise sources	Being evaluated

7. HP activities in mm-waves

HP now has a fairly complete line of instruments and components to make measurements up to U-band, 60 GHz in...

- **Power (up to 50 GHz)**
- **Spectrum Analysis**
- **Network Analysis**
  - **Vector**
  - **Scalar**
- **Signal Sources**
- **Frequency (up to 40 GHz)**
- **Measurement Accessories**

8. HP traceability at mm-wave frequencies

A. Impedance

- Indirect traceability to NBS thru dimensions of Sliding load and offset shorts

B. Attenuation

- Indirect traceability to NBS thru parallel IF (30 MHz) substitution

  30 MHz piston attenuator is calibrated by NBS

8. HP traceability at mm-wave frequencies

C. Power

- Direct traceability to NBS
  CAL-factor of HP standard power sensor is calibrated at several frequencies by NBS.
- Indirect traceability
  CAL-factor of HP standard power sensor is calibrated internally, at every GHz, with a calorimeter.

D. ENR

None at this time.

E. Frequency

- Indirect traceability by linear down conversion

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8. HP Traceability at mm-wave frequencies

Impedance

	Standards lab			Production		
	Msmt method	Standard reference	Uncertainty	Msmt meth	Standard reference	Uncertainty
K_a-band 26.5-40 GHz	Manually tuned Reflectometer	Dimensions of sliding load calibrated with laser interferometer	0.006 +0.014 Γ_D	ANA ↓	Sliding load calibrated at standards lab ↓	0.006 + 0.014 Γ_D
Q-band 33-50 GHz	Manually tuned Reflectometer (ANA) future	↓	0.007 +0.017 Γ_D	↓	↓	0.007 + 0.017 Γ_D
U-band 40-60 GHz	ANA future	↓	0.009 +0.02 Γ_D	↓	↓	0.009 + 0.02 Γ_D

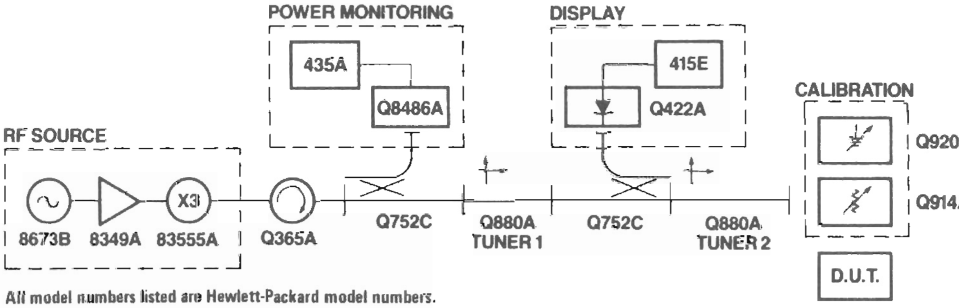
8. HP Traceability at mm-wave frequencies Attenuation

	Standards lab			Production		
	Msmt method	Standard reference	Uncertainty	Msmt meth	Standard reference	Uncer-tainty
K_a-band 26.5–40 GHz	Parallel IF substitution	Piston Attenuator calibrated by NBS	0.03 +0.02/10 dB	ANA	IF attenuator of ANA	0.03 + 0.02/ 10 dB
Q-band 33–50 GHz	↓	↓	0.04 +0.03/10 dB	↓	↓	0.04 + 0.03/ 10 dB
U-band 40–60 GHz	↓	↓	0.05 +0.03/10 dB	↓	↓	0.05 + 0.03/ 10 dB

8. HP Traceability at mm-wave frequencies Power

	Standards lab			Production		
	Msmt method	Standard reference	Estimated worst case uncertainty	Msmt meth	Standard reference	Estimated Uncertainty tainty
K_a-band WR-28 28–40 GHz	Manually tuned reflectometer	Thermistor sensor calibrated by NBS	CAL factor ≈ 2%	ANA	Power sensor calibrated at standards lab	–
Q-band WR-22 33–50 GHz	↓	R-band thermistor sensor Q-band thermocouple sensor Q-band calorimeter	CAL-factor ≈2.3% 40 GHz ≈5.5% 50 GHz	↓	↓	40 GHz ≈3.9%, R.S.S. ≈6.8% W.C. 50 GHz ≈5.5% R.S.S. ≈9.3% W.C.
U-band WR-19 40–60 GHz	–	–	–	–	–	–

9. Manually Tuned W-G Reflectometer. HP Standards Lab Calibration Set Up



All model numbers listed are Hewlett-Packard model numbers.

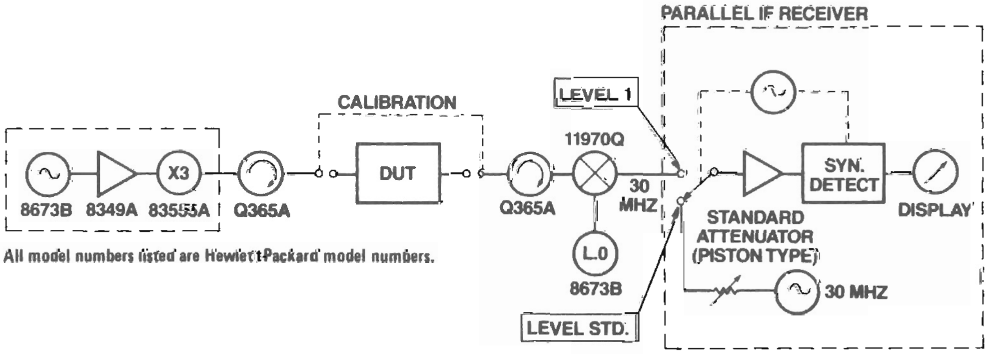
System Calibration Procedure

1. Set source match equal to Z_0 with tuner 1 and sliding short.
2. Cancel directivity with tuner 2 and sliding load.
3. For power calibration, determine incident power with standard power sensor. Calibrate sensor under test against the incident power.

Calibration Consideration

1. HP Q422A must operate in square law range.
2. HP 415E must be calibrated.

10. Parallel IF Substitution. HP Standards Lab Calibration Set Up.



All model numbers listed are Hewlett-Packard model numbers.

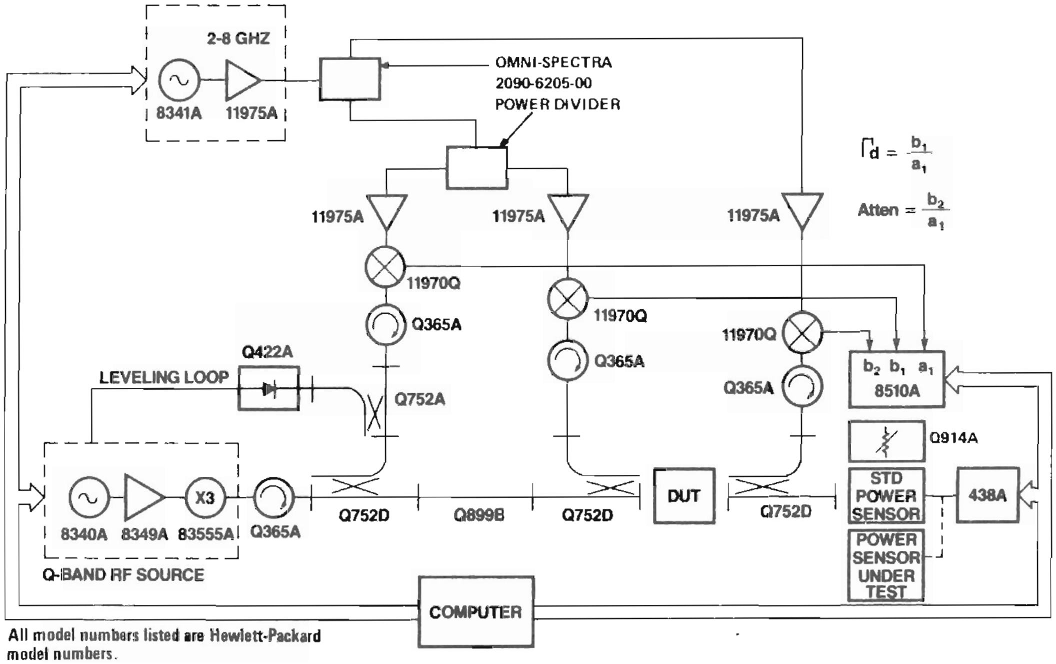
Measurement Procedure

1. If level 1 = level std., the display will read zero.
2. Set attenuation reference by adjusting standard attenuator for null indication on display.
3. Insert device under test. Adjust standard attenuator for null indication again.
4. Difference of standard attenuator reading between 2 & 3 above is the calibrated value of device under test.

Calibration Considerations

1. Mixer must be operated in its linear range.
2. Source and load match affect accuracy.

11. System Configuration For Q-Band Calibration In HP Production Impedance, Attenuation, and Power



All model numbers listed are Hewlett-Packard model numbers.

12. HP mm–wave calibration services

A. At this time, HP only provides re–calibration services for HP products up to 60 GHz, unless otherwise listed. Re–calibration is done in production only.

B. The re–calibration services are for the following parameters:
- CAL–factor of power sensors (up to 50 GHz)
- Reflection coefficient
- Attenuation
- Directivity

12. HP mm-wave calibration services

C. A report will be issued giving the calibrated parameters as a function of frequency at least at every GHz, including uncertainties.

D. At this time HP does not comply with MIL-STD-45662.

12. HP mm-wave calibration services for Q-band 33 to 50 GHz

	Estimated accuracy	Number of points	Price	Comments
CAL-factor of power sensors	3.9% RSS 40 GHz 6.8% w/case 40 GHz 5.5% RSS 50 GHz 9.3% w/case 50 GHz	18	$150	Includes reflection coefficient
Reflection coefficient	0.007 +0.017Γ_D	51	$100	
Attenuation	0.04 +0.03/10 dB	51	$150 per atten setting	Includes reflection coefficient
Directivity of single couplers	Limited by measuring system effective directivity of 43 dB	51	$300	↓

USA prices

12. HP mm–wave calibration services for U–band 40 to 60 GHz

	Estimated accuracy	Number of points	Price	Comments
CAL–factor of power sensors	–	–	–	Not available at this time
Reflection coefficient	$0.009 + 0.02\Gamma_D$	51	$115	–
Attenuation	0.05 +0.03/10 dB	51	$175 per atten setting	Includes reflection coefficient
Directivity of single couplers	Limited by measur–ing system effective directivity of 41 dB	51	$350	↓

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12. HP mm–wave calibration services

Procedures to get products re–calibrated:

Send them to your nearest HP service office.

LIST OF REFERENCES

1. G.R. Reeve and C.K.S. Miller, *Current NBS Capabilities and Limitations at Millimeter Wave Frequencies*, Measurement Science Conference, January 1985.
2. NBS Technical Note 642.
3. Hewlett-Packard Product Note Number 8510-1.
4. Edward L. Ginzton, *Microwave Measurements*, McGraw Hill, 1957.
5. IEC-standard publication 154-2, 2nd edition 1980.