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Product Note 33

ALPS-308, Active Load Pull System for PCN Applications

ALPS is a Load Pull system for fast and simple-to-use measurements on power devices with ***reflection factors up to 1 at any reference plane***. The first member of the ALPS family is ALPS-308. It performs load pull measure-ments up to 1 Watt from 0.8 to 3 GHz, S-parameter measurements from 0.5 to 4 GHz and has ***Harmonic Tuning capability***. ALPS works with and ***expands the large signal measurement capability of automatic network analyzers.***

System Description

ALPS employs an ***active load technique*** in which the output signal from the Device Under Test (DUT) is sampled, modified with respect to phase and amplitude and fed back into the output port of the DUT. This emulates a complex load for the DUT with reflection factors up to 1 at any reference plane. Depending on the options selected ALPS includes in one 19" rack enclosure:

- A medium power input driver amplifier and internal fused bias tees.
- A remotely controlled input tuner for device pre-matching.
- A RF switching matrix for in situ measurement of incident and reflected waves to the DUT under any load conditions (Reflectometer).
- An active load with 1 Watt power capability (*User increasable*).
- Windows® 3.1 or 95 control software for S-parameter, DC-parameter and Load Pull contour measurements of P_{IN}, P_{OUT}, Gain, Efficiency, Intermod and Adjacent Channel Power (ACP), Data processing, Contour and Saturation plots.

ALPS is compatible with all network analyzers of Hewlett-Packard® and Wiltron®, to which it interfaces simply by means of two RF cables linked to the test ports.
Calibration (TRL) is straight forward for fixture or wafer measurements and takes less than five minutes. ALPS generates Γ up to 1 at DUT reference plane practically independent on cable and probe loss. ALPS typically measures 1000 points in as little time as 2 minutes (150ms/point). ALPS' power capability can be increased by inserting power end-stages in the active load (externally accessible).

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System Operation

ALPS operation is controlled by an IBM®-PC model 486 or higher with at least 4MB of RAM. This computer includes also a GPIB and an ALPS Interface Bus (AIB).
ALPS has the following capabilities:

■ Optimizes the load conditions automatically for best coverage of the Smith Chart up to |Γ|=1.
■ Runs load pull measurements for preselected load phase, |Γ| and input power values.
■ Generates results that can be saved in a data bank and plots can be generated in 2D contour, 3D surface or Pout/Pin formats at any impedance point.
■ Includes a Mapping capability that identifies load impedances fulfilling predefined power, gain, efficiency criteria.
■ All data files can be converted to other popular formats.

ALPS operates together with a vector network analyzer, which is used as a signal source and fast receiver (figure 2). ***ALPS adds load pull measurement capability to a vector network analyzer.*** There are no internal modifications to be made to any of the supported network analyzers in order to connect to ALPS. For control they have to be connected to the GPIB and to ALPS' trigger output. The same is valid also for other equipment used, such as the digital Multimeters for efficiency measurements.
A true power meter is required only during system calibration to determine reference power levels. Spectrum analyzers can be connected at RF port AUX on the back panel of ALPS and allow for Intermod/intercept and adjacent channel power measurements (fig.2). Neither the network analyzers need to be calibrated for ALPS to operate, nor are calibration standards, other that TRL required. The complete calibration and measurement operation is controlled by the IBM-PC, which also holds the system calibration data (error coefficients) and processes the load pull and S-parameter data files.

The block diagram on figure 2 shows how ***ALPS operates as part of a network analyzer-based load pull setup***. A spectrum analyzer (if used) is connected to the RF port AUX.

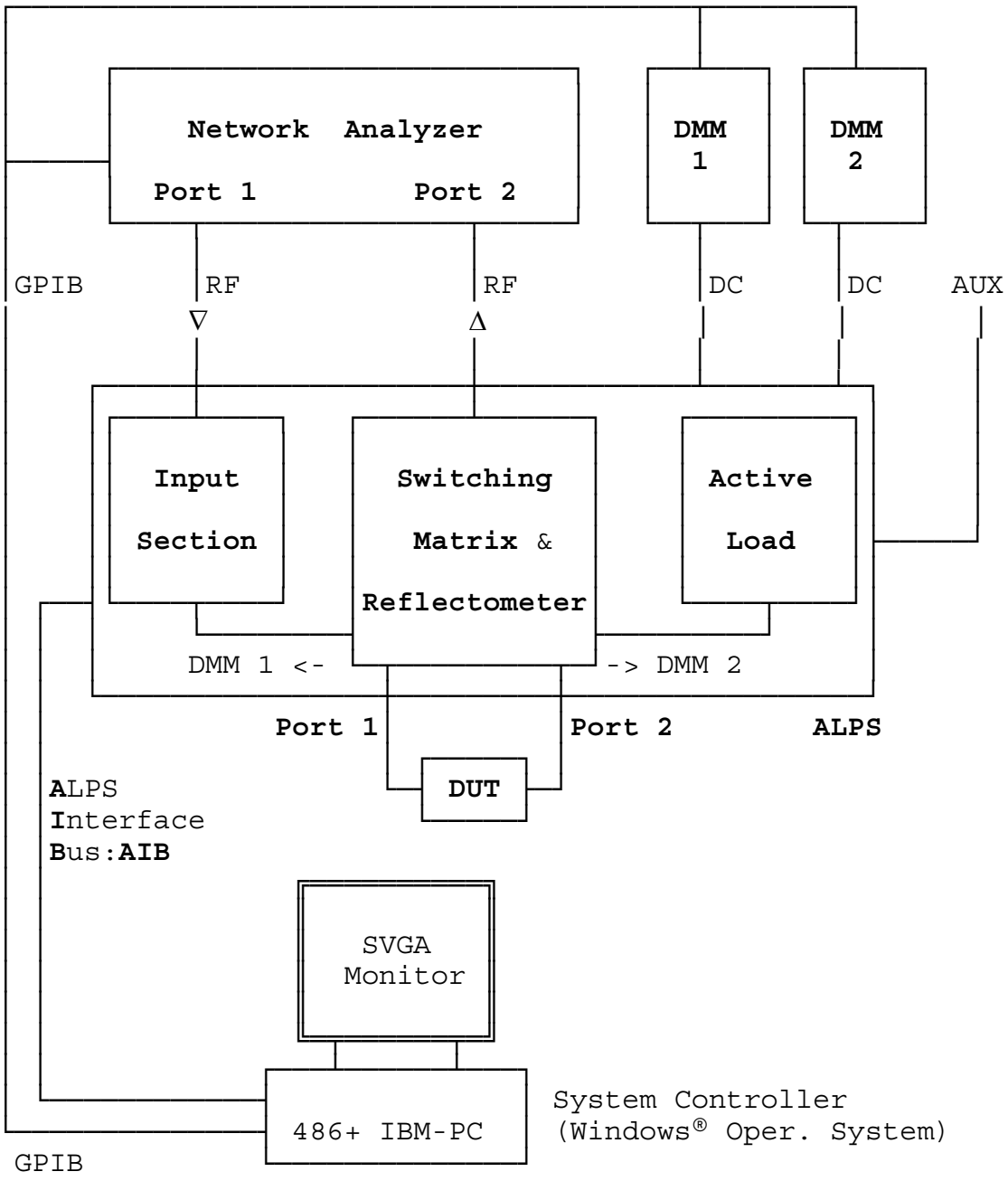


Figure 2: ALPS allows to build a ***Load Pull and (large signal) S-parameter Measurement System using any Vector Network Analyzer***

Active Load

There are two possible concepts in order to build an active load pull system. The ***split signal method***, known also as "Takayama" technique, and the ***Active Load technique*** [2].
The split signal method uses a power splitter after the RF source and permits to inject half of the RF power, amplified and de-phased, into the output of the device, simultaneously with the other half, which is injected into the input port. The problem of this method is that it is impossible to sweep the input power to the device for $|\Gamma_L|$=const, since when the DUT saturates and its gain changes, this cannot be tracked by the gain of the direct signal path and the system should be recalibrated for every single input power level. This is very detrimental for power saturation and gain compression tests.
The ***active load technique*** samples the outgoing signal from the device using a directional coupler, amplifies it, modifies its phase and re-injects it into the output port of the device. This way a load reflection factor of up to 1 or even larger can be generated. The advantage of this method compared to the split signal method is that the load reflection factor does not change when the input power changes and the DUT saturates, thus allowing accurate and simple gain compression tests. The disadvantage of this method is that the active load may oscillate at parasitic frequencies if not properly filtered and gain limited. ALPS uses the ***active load technique*** in order to generate a complex reflection factor at the output of the device:

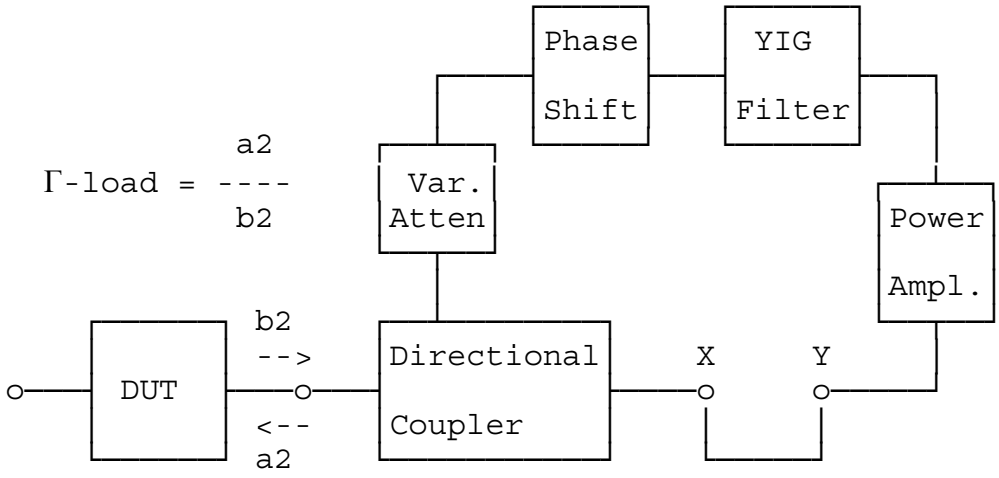


Figure 3: Concept of *Active Loop* Load used in ALPS

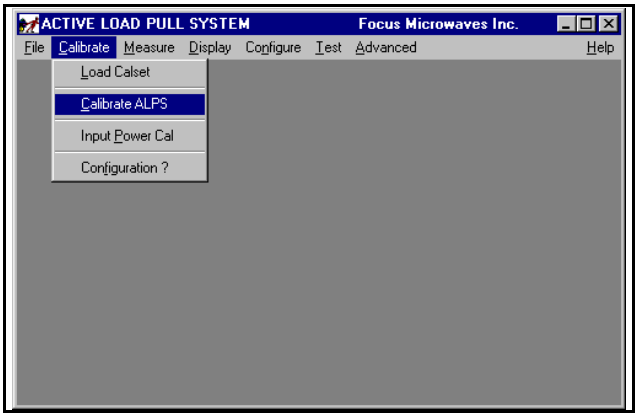
All components of the active loop such as variable attenuator, phase shifter and YIG filter are controlled by the ALPS motherboard electronics, which communicates via AIB with the system PC controller. The variable attenuator controls the magnitude of Γ_{Load} and the phase shifter the phase. The YIG filter being tuned at the operation frequency prevents the active loop from oscillating. The active loop of ALPS can be interrupted from outside between points X and Y so the user can insert an additional high power amplifier stage in the loop in order to increase the power capability of the system.

ALPS Software

ALPS software is written in "C++" programming language in Windows® operating system for PC's. It can be executed equally from Windows® 3.1 or 95. The executable program used for ALPS is called *WINALP*. It controls all user interface, calibration and measurement functions and communicates with associated software packages that handle the contouring and the cartesian data display.
WINALP is structured in functional menus as follows:

Menu	Operations performed
• **Calibrate**	Load existing Calsets or Calibrates the system
• **Measure**	Measure Load Pull, S-parameters and DC-parameters
• **Display**	Generate Contours, S-parameter and DC-parameter plots
• **Configure**	Define Working Directory, GPIB Instruments, File names etc..
• **Test**	Check most ALPS functions and system performance
• **Advanced**	Adjust and verify critical operation parameters of ALPS
• **Help**	Display Help topics on the operation steps

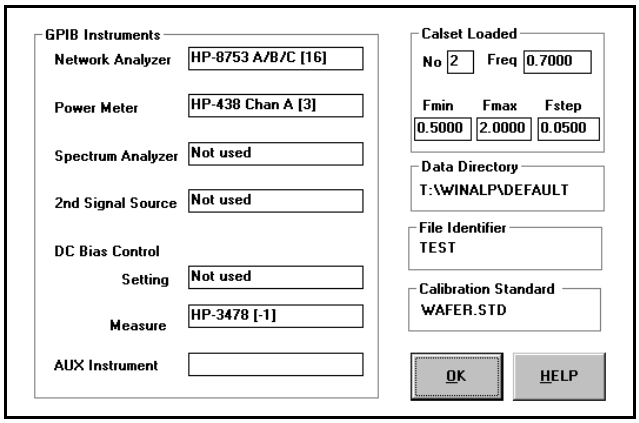
ALPS's main Windows menu gives structured access to all the above operations.



Auxiliary software (Windows Applications) includes FGRAPH for Saturation and S-parameter (Smith Chart) plots and ALPCONT for contouring of Load Pull files [see pages 11-14].

ALPS's software is organized around Menus and Dialogues. Figure 4 shows the Main menu and the pulldown Calibration menu.

Very useful for the operation is the configuration dialogue (figure 5). It gives a rapid and effective overview of all impor- tant operation parameters.



Calibration of ALPS

ALPS includes a ***Twoport Reflectometer*** that permits the measurement of incident and reflected waves both at the input and the output port of the DUT. ALPS can also measure true injected and reflected power at both DUT ports. All measurements during operation are made using the network analyzer. In order to be able to do this ALPS must be calibrated, including the cables and test fixture (or wafer probes), with reference to the DUT ports.
Small signal calibration is performed by connecting and measuring TRL calibration standards THRU, DELAY, REFLECT (Open or Short) at the DUT reference plane.
The S-parameter of the THRU, DELAY and REFLECT are measured and TRL theory is applied in order to deduct error coefficients of the 8-term model of both sides of the Reflectometer.
RF power measured at the calibration port is corrected by the error terms and permits to compute the correction coefficient between the network analyzer reading and true RF power injected and reflected at the DUT ports [5]. The 8-term model used in the implementation of this calibration technique is shown on figure 6:

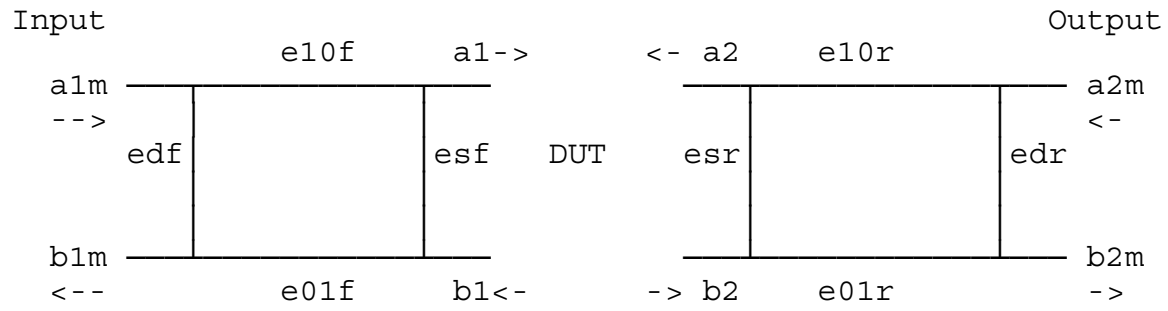


Figure 6: Eight term Error Model used to calibrate ALPS

The S-parameters of the two error twoports are computed from measurements of the Reflectometer parameters at two different load conditions with a THRU LINE standard connected between the two DUT ports. This generates a set of equations (1) to (4) for each standard (THRU, DELAY, REFLECT) connected and permit to compute the 8 error terms.

$$b1m = a1m*edf + b1*e01f \quad (1)$$

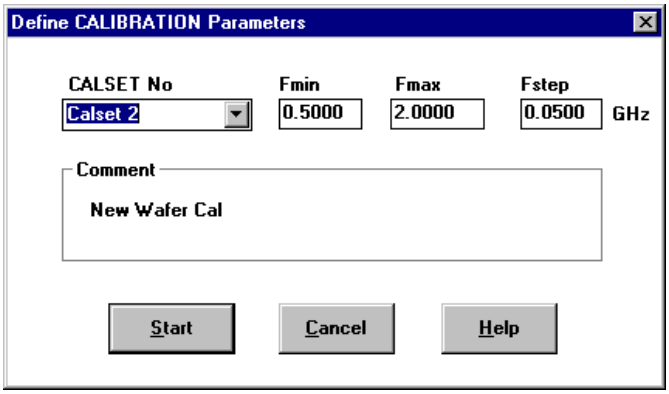
$$a1 = a1m*e10f + b1*esf \quad (2)$$

$$a2 = b2*esr + a2m*e10r \quad (3)$$

$$b2m = b2*e01r + a2m*edr \quad (4)$$

Using the above error coefficients and by connecting a GPIB power meter on the *Calibration Port* of ALPS we can calibrate also for *true power at the DUT reference plane.*

The Calibration Dialogue of ALPS permits to define the calibration parameters and execute a calibration or select and load an existing CALSET. The error coefficients computed during the calibration of ALPS are valid as long as the setup between the DUT ports of ALPS and the DUT is not mechanically modified. These error coefficients are used both for S-parameter measurements of the DUT (view into the DUT) as well as the reflection factor of the Active Load measurements (view into the load).



Source Tuning

ALPS has source tuning capability. Experimental setups described up to now in the literature [1,2,3,4] do not offer this possibility. In fact their main purpose has been to prove that the concept works. The active load concept, on the other hand, cannot be extended to source tuning in the same setup. Without source tuning large amount of RF power must be injected into the input of the DUT in order to saturate it. ALPS uses for this purpose a modified version of one of FOCUS' mechanical tuners, remotely controlled by the same computer and software using ALPS Interface Bus (AIB). This tuner is connected right behind the input Reflectometer in order to minimize the insertion loss up to the DUT ports and, thus, maximize the VSWR tuning range. Using this tuner allows to prematch many DUTs and save up to 90% of injected power which otherwise would be required in order to saturate the device using a 50 Ω source.

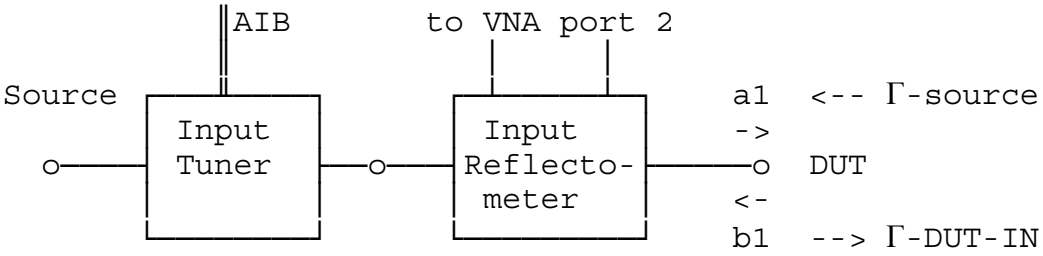
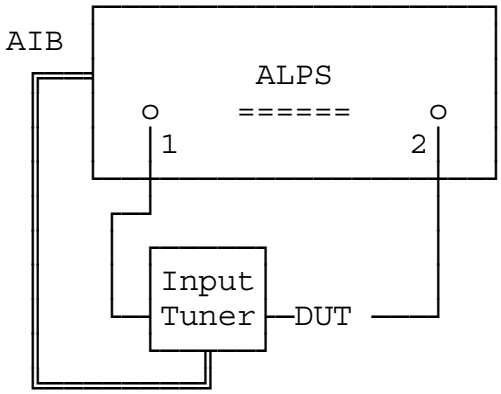


Figure 8: Configuration of passive input tuner *inside the ALPS module*

The input tuner is used only for prematching the device. When the device is nearly matched at the input the reflected power $|b1|^2$ becomes small and we can assume that $\Gamma_{DUT\text{-}IN} \approx \Gamma_{source}^*$,

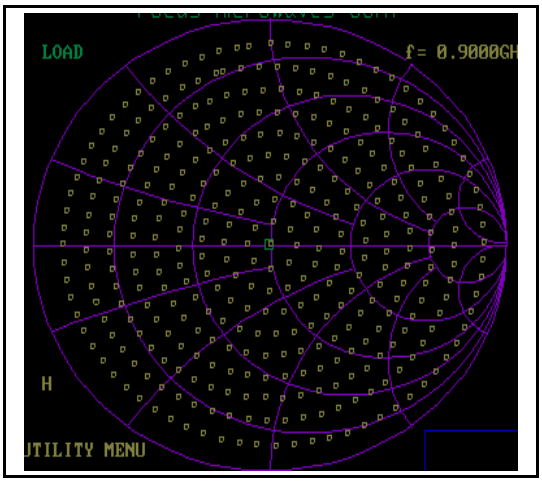
whereas Γ_{source} is the source impedance presented to the DUT by the setup and the input tuner. This impedance is displayed by WINALP when the Operator tunes the input tuner to prematch the DUT.
Due to cable losses, especially for on-wafer measurements, the tuning range of the input tuner at DUT reference plane is reduced. The tuner itself may generate VSWR up to 20:1 but, depending on these losses the VSWR may be reduced to less than 10:1 at DUT reference plane.
A practical way to *increase the source VSWR tuning range* at the input port of the DUT is to *install an automatic tuner very close to the device*, outside of the ALPS box. This may require a special positioner in the case of a probe station. Electronic control of the external tuner is the same whether the tuner is inside or outside the box. Once the question of the mechanical setup has been solved by the User, ALPS provides a special calibration technique that permits to calibrate the external tuner frequency by frequency [6] and use the calibration data of the tuner itself and the test fixture (wafer-probes) to tune to a specific impedance in order to prematch the device under test. The S-parameter data of the input tuner at each position are used to correct the injected and reflected power measurements of the network analyzer to the reference plane of the DUT.



1,2 = DUT port 1,2 of ALPS

TC = Tuner remote Control

Figure 9: *External input tuner* connected close to DUT reference plane



The routines used to calibrate the external (passive) tuner use the same algorithm as the routines of Focus' CCMT system [6]. This allows an optimum coverage of the Smith Chart at every frequency. This is necessary in order to be able to fine tune the input of the transistors and obtain optimum performance [7]. Figure 10 shows a pattern of calibration points of the input tuner of ALPS when connected externally. It is important to note that the software can compute the right positions of the tuner axes for any impedance between the calibrated points and position the tuner so that it can synthesize this impedance with sufficient accuracy (≈40dB).

Harmonic Tuning using ALPS

System	$\|\Gamma_L(f_0)\|$	$\|\Gamma_L(2f_0)\|$	$\|\Gamma_L(3f_0)\|$
ATN	≤0.8	≤0.69*	≤0.6
H-ALPS	1.0 _	1.0 _	1.0 _
CCMT**	≤0.9 _	≤0.8	≤0.85
Required	**>0.9**	**>0.95**	**>0.95**

* Not all phases.
** Using Low Loss Multiplexer and Transformer.

It has been reported that presenting to the transistors specific load impedances at the *second and third harmonic frequencies ($2f_0$ and $3f_0$)* may improve its gain and in particular the Power added Efficiency by roughly 10%, especially in class A-B, B and C operation. This happens when ***most of the power at those frequencies is reflected back into the device with an optimum phase***. The load reflection factors at $2f_0$ and $3f_0$ should therefore be close to 1. This has been recently confirmed from computations based on nonlinear models [8]. Table 1 shows a comparison between actually available solutions to Harmonic Tuning.
Active Load Pull has the capability of harmonic tuning by adding active load loops at the harmonic frequencies and tuning the network analyzer to measure those.

The harmonic Tuning option ALPS 308-H configuration is shown in figure 11:

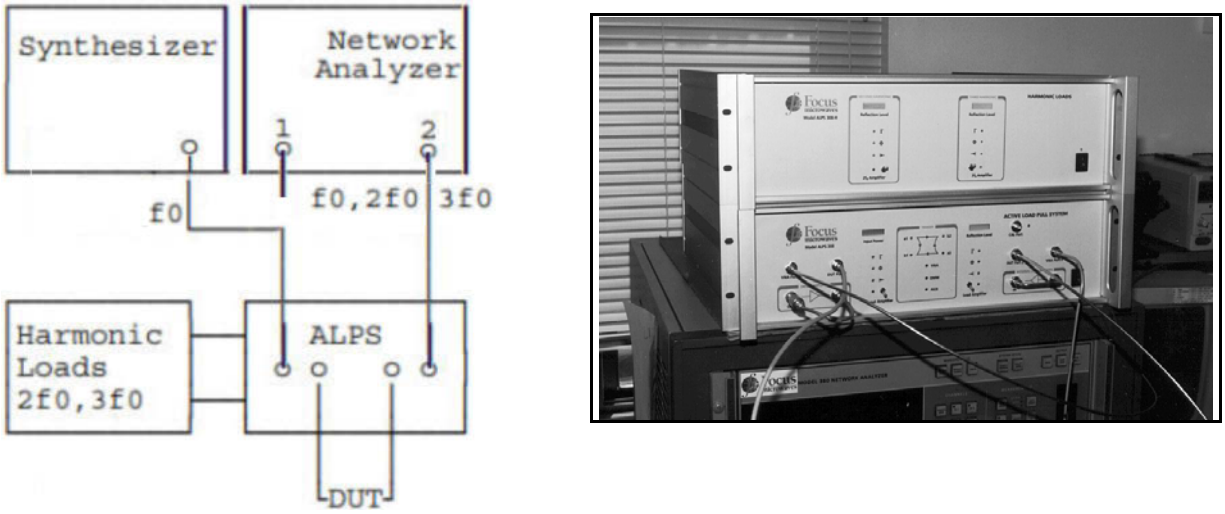
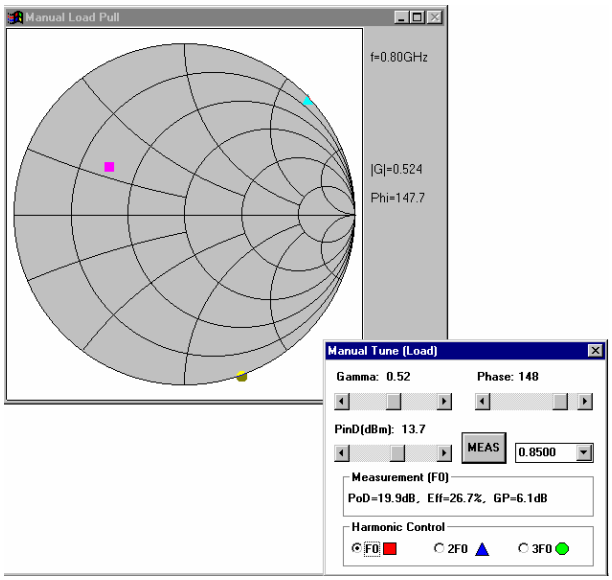
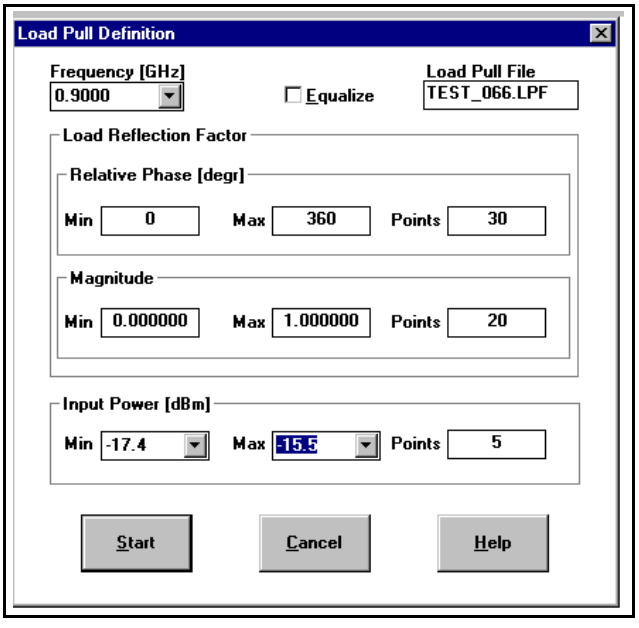


Figure 11: Setup for Load Pull and Harmonic Tuning using ALPS



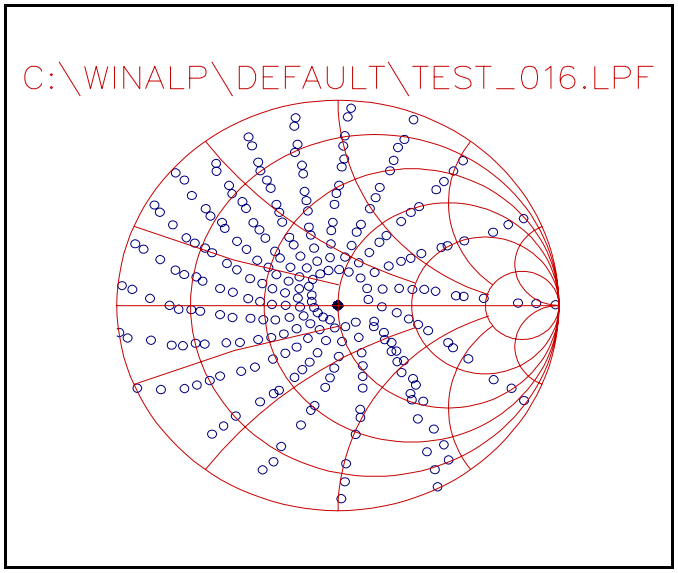
The harmonic load pull setup includes, besides ALPS and the active load at the fundamental frequency f_0, also an external synthesizer, connected at port 1 of ALPS and the external unit "***Harmonic Loads***". This unit includes the active loads for the frequencies $2f_0$ and $3f_0$, and works on the same principle as the fundamental load. The harmonic signals injected into this unit are sampled and filtered out of the basic ALPS unit at the output port of the DUT.
All components are controlled by the same PC via AIB and GPIB. By selecting the frequency of the reference synthesizer inside the network analyzer we have access to the load impedance on either of the harmonic loads independently. The actual status of each harmonic load is controlled independently from the PC controller via AIB, which adjusts the value of the phase shifter and attenuator in each active harmonic loop ($2f_0$ and $3f_0$). ***Manual Load Tuning*** permits to alternatively select one of the harmonic loads and tune to a point of the Smith Chart and measure the DUT's performance at the fundamental frequency without affecting the loads at the other frequencies.

Load Pull Measurements



ALPS performs load pull measurements by adjusting the phase and amplitude of the active loop in order to re-inject the right amount of signal power into the output of the device. Fully independently on this, ALPS can sweep the power injected into the device in order to measure Gain Compression characteristics. The load reflection factor Γ_{Load} stays constant during this sweep because the power returned from the load (a2) only depends on the power leaving the device (b2). An automatic *scaling* routine scans all phases and amplitudes of the complex load Γ_{Load} and adjusts the gain of the loop such that the maximum reflection factor at device reference plane *does not exceed 1*. This is done every time the calibration is changed or

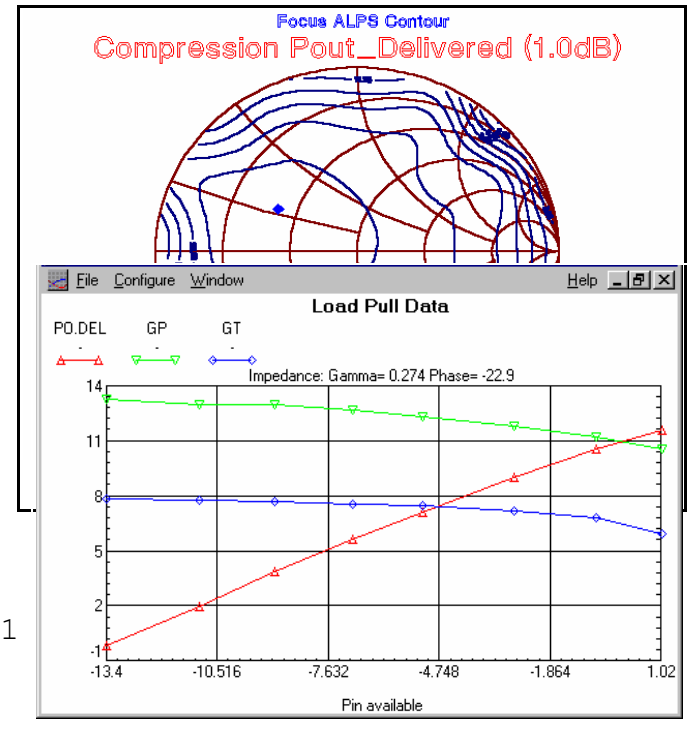
at any new frequency of operation and helps prevent the transistors from oscillating.
The number of load pull impedance points is not limited by hardware. There are limitations by software, though, in order to avoid huge data files. The software is actually limited to 30 phases x 25 amplitudes x 20 input power levels per load pull test (15,000 data points). Every combination below this limit can be selected in the corresponding dialogue box (figure 13).



During the measurement ALPS acquires the two incident and the two reflected waves into the DUT (a1,a2,b1,b2) and the DC bias (V1,V2,I1,I2), if a digital multimeter is connected. This data are saved in a Load Pull File (.LPF) and can be processed afterwards to Gain, Power, Efficiency contours at different input powers. Because both the incident and reflected power waves into the DUT are measured, ALPS can compute the ***real Power Added Efficiency*** *(PAE)* at any load and source impedance point. Passive precalibrated load pull systems (like the CCMT and MTS of Focus) cannot do this. There is no practical way as to measure the real reflected power from the DUT in a load pull setup, except to use an "in situ" Reflectometer, as ALPS does. In passive systems PAE can only be measured if the DUT is matched at the input port and this requires high resolution tuning capability [7].

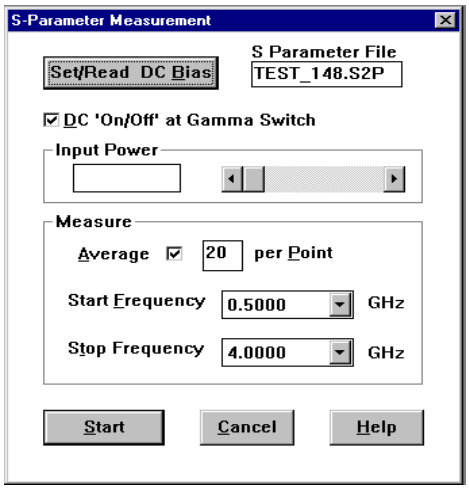
Gain Compression Load Pull

Real gain compression load pull is an important though not obvious task. It is not enough to tune the DUT to maximum gain, increase input power until gain compression is reached and then run normal load pull at constant input power. In fact the correct test involves, normally, an input power sweep at each tuned load impedance. In passive load pull systems, which set input power through GPIB commands of the signal source and read power from RF power meters, this task is quite lengthy, depending on the resolution of input power sweep selected. ALPS,



however, uses internal electronic input power control with instantaneous response time in the ms time range. The directly triggered VNA power acquisition also enables very fast power readings. The result is an average measurement speed of about 120ms per point. This normally includes all tuning and input power setting operations of a complete load pull measurement. After the load pull is terminated Gain Compression Load Pull consists of data
selection in the .LPF (Load Pull File), for the right gain compression selected. The final result is saved in a memory file which is then processed to contour plots. At each selected load impedance the data of the .LPF file can also be processed to Pin/Pout plots on the screen using the Display Menu.

S-Parameter Measurements



ALPS includes a ***calibrated twoport Reflectometer***. This permits to measure full twoport S-parameters of active and passive twoports, such as attenuators, test fixtures, transistors, cables, couplers and isolators. There are two possibilities for measuring twoport S-parameters:

1- Inject the source signal at the input and output port of the DUT and measure injected and reflected power waves. This requires the RF signal to be internally switched from port 1 to port 2.

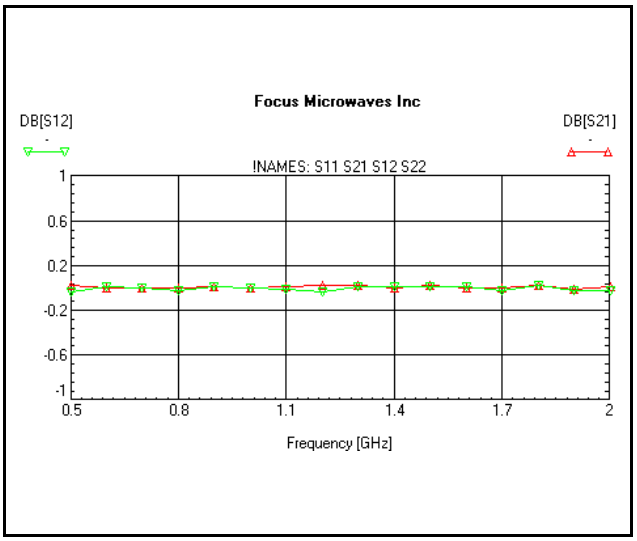
2- Measure injected and reflected power waves at input and output port of the DUT under two different load conditions Γ_1 and Γ_2.

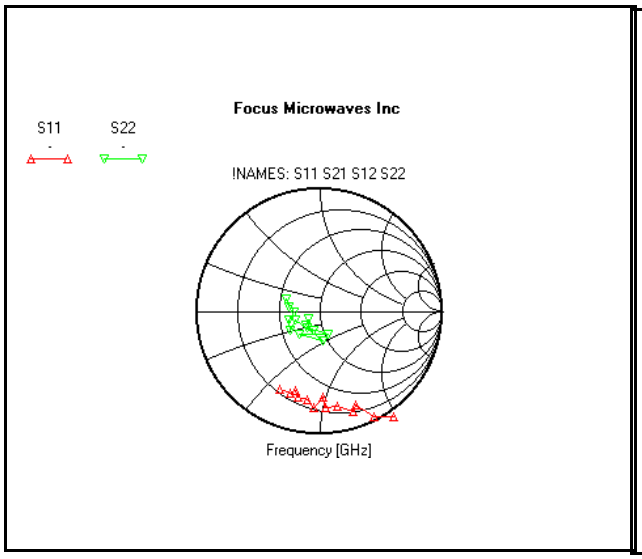
This later technique is better suitable to ALPS, since we have simple control of the load conditions switching between the CAL port and the active load port. The choice of Γ_1 and Γ_2 is not trivial, however, since the device may oscillate under certain conditions.

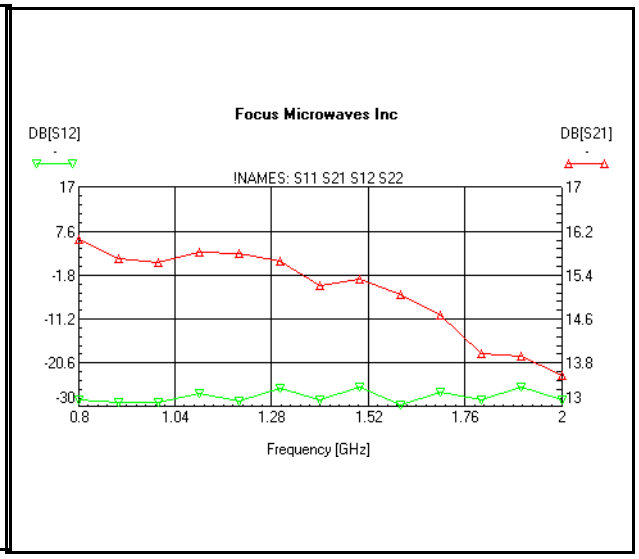
Using the second method we can measure the ***"S-parameter" of the DUT under large signal conditions***. This will provide meaningful results only if the behaviour of the DUT does not change significantly between the two load conditions Γ_1 and Γ_2. If this is the case then the result will be an average value between the two states.

The RF bandwidth of the components used in ALPS-308 permit S-parameter measurements in a frequency range wider than the instantaneous load pull frequency range, which is mainly limited by the power amplifiers used. This S-parameter coverage extends from 0.5 to 4 GHz.

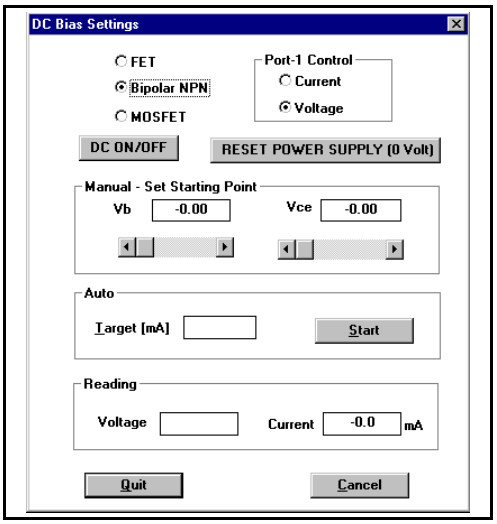
The ***Display*** utility of ALPS permits Cartesian, Polar and Smith Chart plots. Figures 18-20 show S-parameters of a bipolar transistor and a THRU-Line (verification of TRL calibration) as examples for S-parameter measurement and display capability of ALPS.



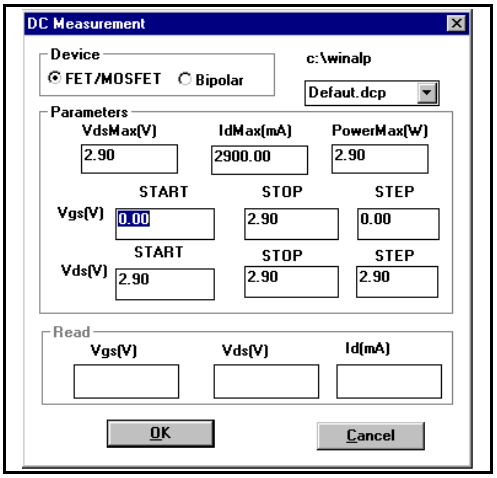




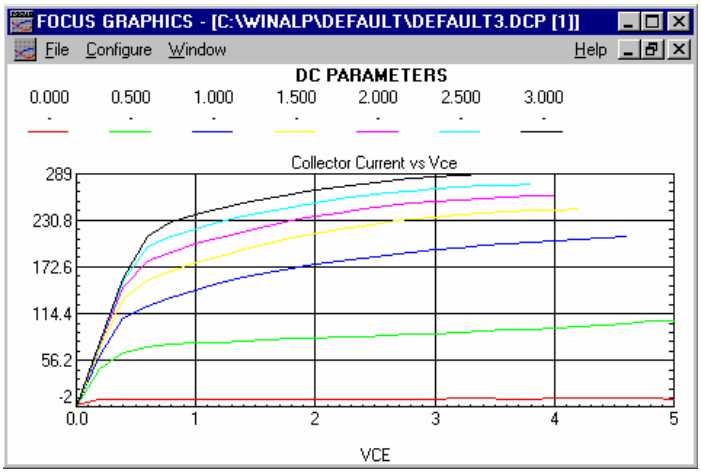
DC-Parameter Measurements



DC-parameters of transistors are used in order to better understand the device and bias it properly. ALPS' control software includes the possibility of ***manually or automatically biasing the transistors.***
The auto-biasing routine allows to set the target current and adjusts the control voltage (or current) automatically using a fast converging algorithm (fig. 21). For complete DC-parameter measurements the corresponding capability of existing DC power supplies (HP-4142) may be used. If the power supply does not have automatic DC curve measurement capability (HP-6624) then ALPS uses an internal automatic measurement routine (fig. 22).



The DC data measured are saved in a ASCII files and the ***Display*** utility of ALPS uses them to generate cartesian plots (fig. 23).
DC-parameters should be measured under 50 Ω load conditions. Attention must be paid when measuring DC characteristics under non 50 Ω conditions, since the transistors may oscillate or the thermal limits of operation may be exceeded. This may result in the destruction of the devices before they can be fully characterized. ALPS's DC-parameter measurement utility provides for User defined maximum allowable DC power dissipated by the transistor.



Specifications of ALPS-308

Frequency Range	Load Pull 0.8-3.0 GHz
	S-parameter 0.5-4.0 GHz
Harmonic Tuning	f_0=0.8-1.0 GHz, $2f_0$=1.6-2.0 GHz, $3f_0$=2.4-3.0 GHz
(ALPS-308-H)	f_0=0.8-2.0 GHz, $2f_0$=1.6-4.0 GHz, $3f_0$=2.4-6.0 GHz
	higher on request
Maximum Output Power	30 dBm (at ALPS reference port)
Maximum Available Input Power	26 dBm (" " ")
Input Tuner (Passive)	Optional
Speed	150 ms / point (VNA dependent)
Maximum Gamma Load	1.0 at DUT reference plane
Number of Loads	Typical 100-500, but not limited by Hardware
Bias tees	30V, 500mA (higher current optional)
Input Power Control	> 20 dB
Interfaces	GPIB and ALPS Interface Bus (AIB) for IBM-PC

Measurement Options

Power, Gain, Efficiency	Yes
Intermod	Optional
Adjacent Channel Power	Optional
TRL Calibration	Yes
S-parameter	Yes
DC Manual/Auto Setting	Yes/Yes
DC-Parameter	Optional
S-parameter plots	Yes
Contour plots	Yes
DC plots	Optional

GPIB Instrument Support

Network Analyzers	HP-8510, 8720, 8753 and Wiltron 360, 37000
Digital Multimeters	HP-34401 (others optional)
Spectrum Analyzers	HP-70000, 8563, 8594, 8566, Anritsu 2601, 2602, 2613, Advantest 3271
DC Power Supplies	HP-6624 and 4142 (others optional)

Measurement/Graphics Software	Windows® 3.1, 95

Literature

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