3.4.1. Accurate and Traceable High Frequency Large Signal Measurements of TwoPorts

This chapter is a copy of:
Marc Vanden Bossche, Hewlett-Packard NMDG, Accurate and Traceable High Frequency Large Signal Measurements of TwoPorts, presentation at the European Microwave Conference, Oct. 4-8, 1999, Munich

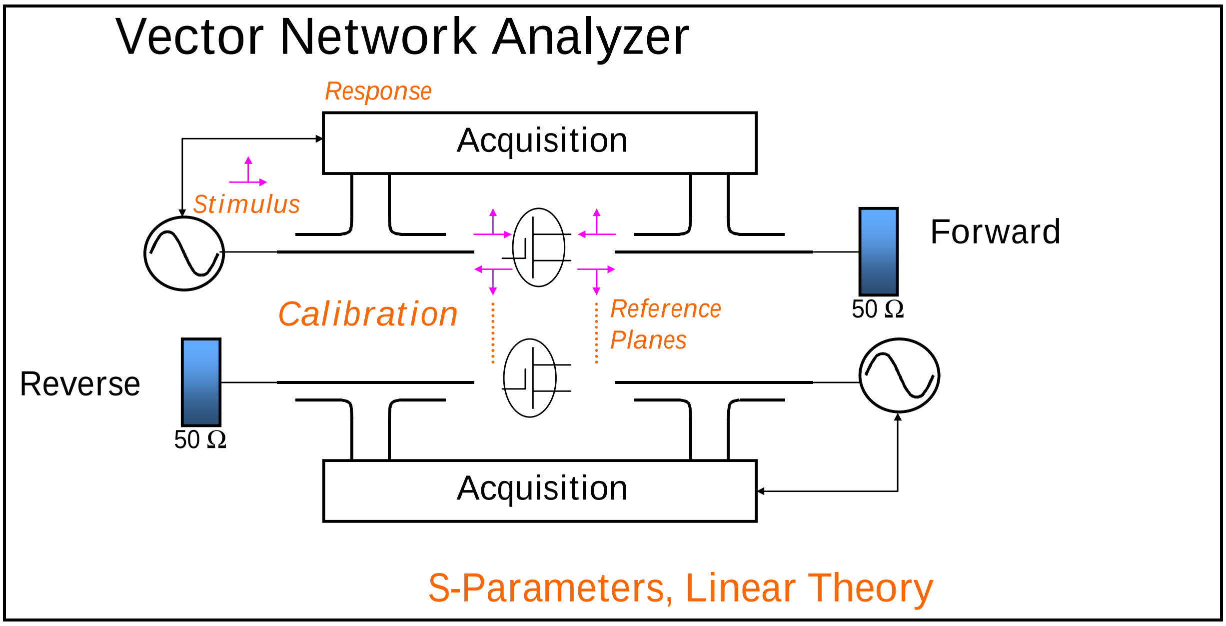
This chapter explains the measurement capabilities of the Nonlinear-Network Measurement System (NNMS) which is a stimulus / response system for the characterization of the large signal behavior of high frequency transistors, components and systems. The NNMS is restricted to two ports.
The known vector network analyzer is used as basis to explain the Nonlinear - Network Measurement System. Some insight in the calibration is provided to understand how the accuracy of the measurements is achieved.

From the design to the manufacturing and testing of components, circuits and systems, there are different phases of concerns and toolsets.
For foundries it is important to develop adequate semiconductor technology that helps evolving to next generations of chips. Speed, reliability and integration level are some of the concerns. It is very important to get insight in the large signal behavior of the transistor in a timely manner to tune the process parameters. Therefore proper device characterization is very important.
A designer relies on simulation tools to synthesize complex circuits. Of course, the simulation tools are only as good as their models. Therefore it is important that reliable models are provided. This is a growing challenge because of the speed of change of the process technology and the complexity of the transistor devices at increasing signal speeds. To create accurate models it is primordial to have good observation tools. Proper and in - depth characterization are the basis for the creation of good models.
During manufacturing and test the characterization of components and systems is again important to check the behavior against specifications. At this level, one will try to simplify the tests as much as possible. Simulation tools can play an important role in simplifying the test cycle as much as possible. But of course the quality of the models determines the relevance of the deduced tests.

Transistor Characterization

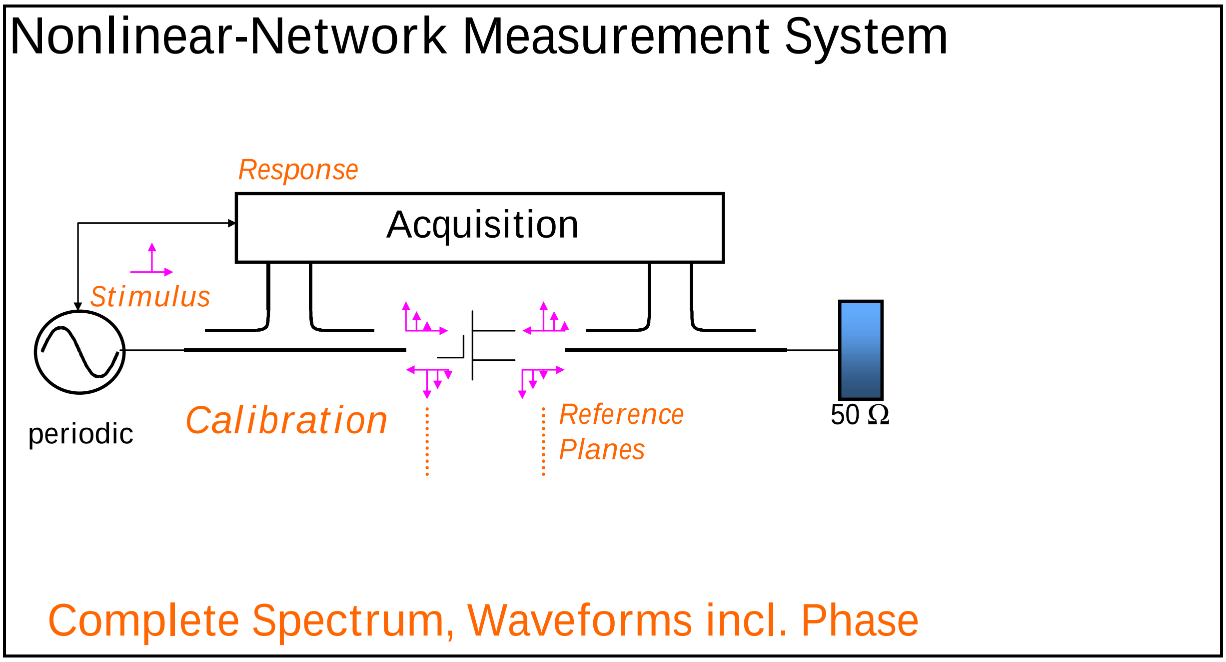
- Static [Digital World]
  - DC I/V Curving
- Dynamic [RF/uwave Analogue World]
  - Small Signal
    - S-parameters (pulsed)
      - ➙ *Vector Network Analyzer (VNA)*
  - Large Signal
    - Power Spectrum : Compression, IP3, ACPR,…
      - ➙ *Spectrum Analyzer, Signal Vector Generator, Signal Vector Analyzer*
    - Time domain : voltage / current waveforms
      - ➙ *Sampling oscilloscopes*
      - ➙ *Microwave Transition Analyzer*
      - ➙ *"Nonlinear-Network Measurement System" (VNA for Large Signal Applications)*

For digital applications, transistors are typically characterized by DC voltage - current measurements. Moving up in signal speed one starts to realize that this is not adequate anymore.
For RF and microwave applications one needs to characterize the transistors dynamically. For small signal characteristics the vector network analyzer did breakthrough from R&D onto the manufacturing floor. S-parameters and small signal behavior are far away from the world of the digital designer who lives and thinks in states and waveforms.
For large signal characterization, one has been interested in compression characteristics, inter modulation, spectral regrowth. These measurements are performed with a spectrum analyzer. The disadvantage is the lack of proper calibration and the restriction to matched environments.
Over time, efforts have been done to measure time domain waveforms. One has been using sampling oscilloscopes and microwave transition analyzers to put measurement systems together.
This workshop explains the Nonlinear-Network Measurement System which is a stimulus / response system, similar to a vector network analyzer but to characterize the large signal behavior completely under a periodic stimulus.



In fact a vector network analyzer is a complete measurement system, containing internally an experiment generation and model extraction capability. The experiment generation consists of a forward and reverse excitation and measurement. The model extraction refers to the equation solving using the measurements, resulting into S-parameters.

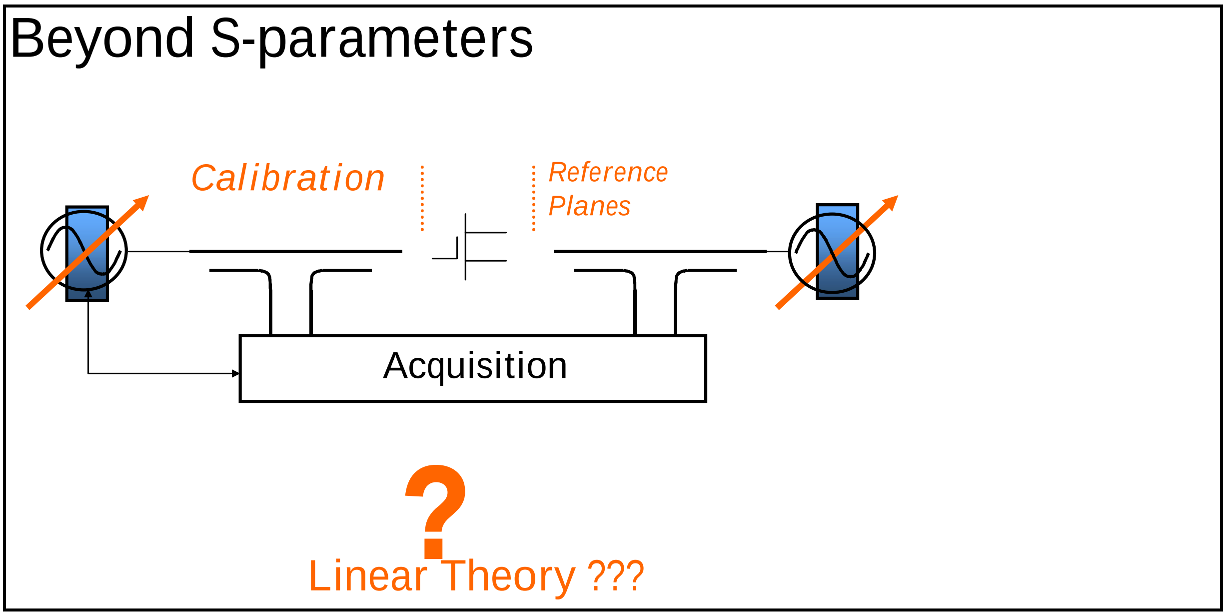
It contains a test - set to separate incident from reflected waves, an acquisition system for uncalibrated measurements and a microwave source. Restricting its usability to linear components and based on the S-parameter theory, a vector network analyzer can internally apply a signal once to the input and once to the output of the device. From these measurements it can calculate the S-parameters using some calibration technique to eliminate the systematic errors introduced by the system.



A Nonlinear-Network Measurement System looks similar to a vector network analyzer. There is a test - set to separate incident and reflected waves. A microwave source can inject a one

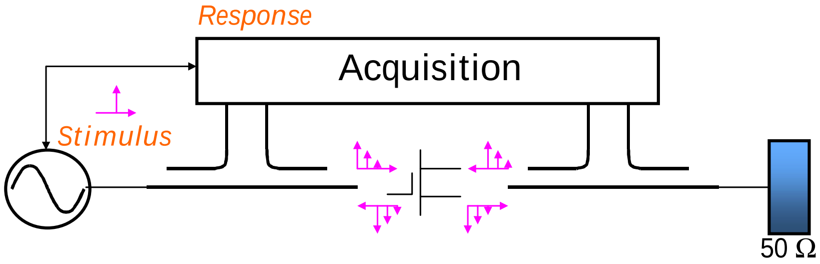
tone signal into a component. If this component is nonlinear, it will generate harmonics. These harmonics are reflected back by the mismatch created by the measurement system. A broadband acquisition system is able to take proper samples of the broadband incident and reflected waves.
With the proper calibration techniques, the systematic errors of the measurement system are eliminated. The complete spectrum (amplitude and phase) of incident and reflected waves can be acquired and the time waveforms reconstructed.

This reflects the real-world performance of the DUT, i.e. changes of the:
    bias conditions
    input power
    load impedance
    stimulus curve trave



Dealing with large signals and nonlinear behavior it is important that more complex stimuli can be presented to the component under test.
The NNMS is able to measure incident and reflected waves under all kinds of conditions. For example, it is possible to ramp the power of the source at the input, to connect a tuner at the output. It is possible to perform active tuning by connecting a second source at the output etc.
Unfortunately there is no generic theory, dealing with nonlinear devices, telling how a limited set of experiments can be performed to extract a generic model, similar to S-parameters.
Research work is going on to come up with models for large signal behavior from large signal measurements under well defined boundaries, restricting components to certain classes.
This research work must help in going “Beyond S-parameters”.

Measurement Example



- Stimulus : 1 tone at 1 GHz
- Acquisition: frequency list
  - 1, 2, 3, …, 20 Ghz
- Incident and Reflected Waves
- Reconstruction of time waveforms

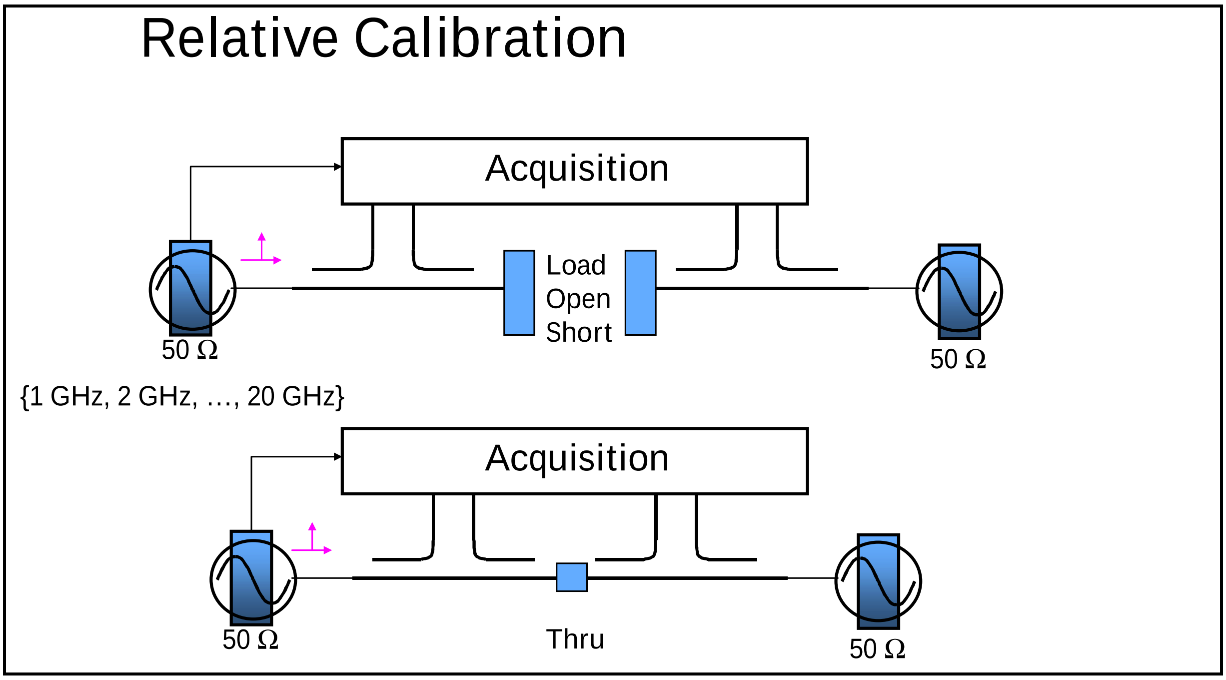
This simple example is used to illustrate some capabilities and terminology. Consider a microwave source, generating a one - tone signal at 1 GHz. The power level is high enough to excite the transistor in its nonlinear region of operation. The transistor starts to generate harmonics. These harmonics are reflected back to the device by the mismatch of the measurement system.
Nevertheless one excites with a one tone, the incident wave to the transistor consists of a large tone and some smaller harmonics. These harmonics cover a set of harmonic related frequencies (frequency grid: 1,2,3,… GHz). In general the measurement system can be configured to detect signals on a frequency grid.
For the NNMS, the lowest possible frequency of the grid is 600 MHz, the highest frequency 20 GHz.
From the amplitude and phase measurements on this frequency grid, the time waveforms can be reconstructed.
Be aware that this is a stimulus / response system using a synchronous detection scheme similar to vector network analyzers. Therefore, spurious signals, not on the frequency grid, are ignored.

Calibration Process

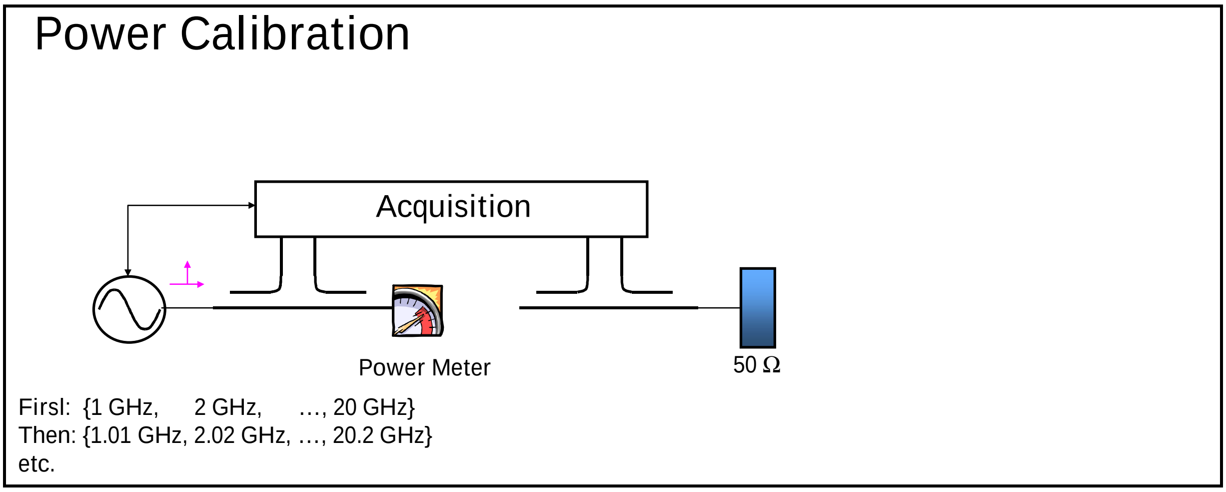
- Relative Calibration
  - similar to VNA
- Power Calibration
  - applied in Loadpull systems
- Phase Calibration

To eliminate the systematic errors, caused by the measurement system, a calibration technique is required similar to vector network analyzers.
It has been proven that first the same calibration techniques from the VNA's are needed to eliminate all errors which have to do with taking ratios between reflected and incident waves. A nice property of linear systems is that only ratios are important.

To measure waves or voltages and currents in an absolute way, two additional calibration steps are required.
First the power distortion as a function of the frequency created by the measurement system must be eliminated and secondly the phase distortion. I.e. the power loss from the synthesized sweeper to the DUT, and reverse.
It is important to remember that all precautions are taken to keep the measurement system itself linear.



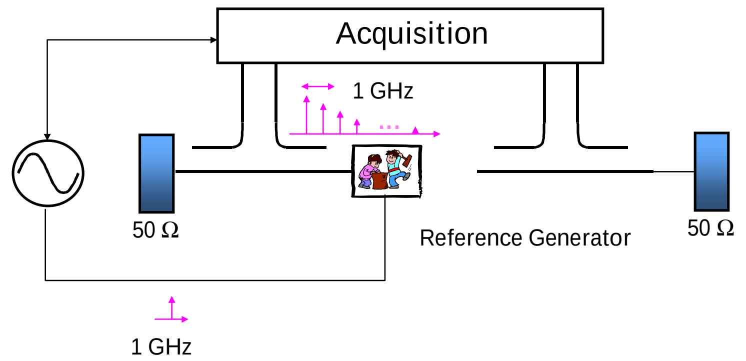
The relative calibration is exactly the same as for a vector network analyzer.
Referring to the example where one wants to characterize a transistor on a frequency grid of 1 GHz with 20 harmonics, the microwave source is stepped in steps of 1 GHz and measuring the S-parameters of known linear devices (load, opens, short, thru).



For the power calibration a power meter is connected to “Port 1” of the NNMS. The source is stepped on the frequency grid. For each step the power is measured and calculated through the acquisition system. This results into a distortion table as function of the frequency.
Measuring on wafer, the calibration reference planes correspond to the probe tips. Therefore, “Port 1” is connected to “Port 2” via a line on wafer and an additional load-open-short

calibration is done at the port with the 50 Ohm load while stepping the source in steps of 1 GHz. Then the power meter is connected at that point and the source is stepped again. With some calculations and the reciprocity principle the power can be referred back to “Port 1”.

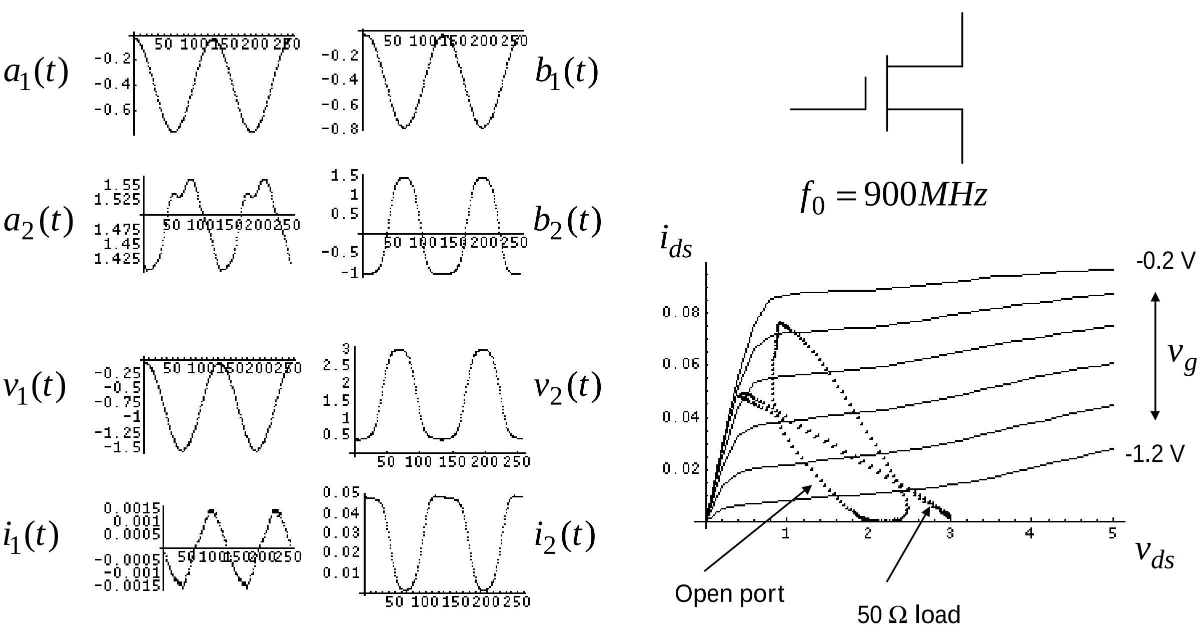
Phase Calibration



For the phase calibration a reference generator is connected to “Port 1” of the NNMS. The source generates one tone at 1 GHz. The reference generator is a pulse generator with a repetition rate of 1 GHz. In the frequency domain this corresponds to spectral components on a frequency grid of 1 GHz. At manufacturing time, HP is capable of calibrating this generator very accurately and traceably with the nose - 2 - nose calibration process in phase.

The calibration process of the NNMS is traceable to standards labs for the relative calibration and for the power calibration. For the phase calibration HP is traceable in - house while NIST is investigating this complete phase calibration process based on the nose - 2 - nose technique.

Measurement Example



With the NNMS in combination with a force / sensing bias supply, it is possible to measure and compare both DC I/V curves and dynamic loadlines.
One can look at incident and reflected waves or voltages and currents in the frequency or time domain.

This leads to the following table of features for the nonlinear VNA compared to a conventional, linear VNA:

Measurement	Simulation	Modeling
VNA	S-parameter calculated out of complex voltages and currents in a Z0 (50Ω) environment	small signal RF
nonlinear VNA	harmonic balance	large signal RF

Publications:

Marc Vanden Bossche, Hewlett-Packard NMDG, Accurate and Traceable High Frequency Large Signal Measurements of TwoPorts, presentation at the European Microwave Conference, Oct. 4-8, 1999, Munich