Remote VSWR & Power Meter

Michael Clemens, DK1MI
mc@qrz.is
Matthias Bopp, DD1US
DD1US@amsat.org

Structure

Introduction

Often there are parts of a radio system where components are operated remotely. Mostly it is only a power amplifier, but sometimes also a transverter or a complete SDR-based transceiver.

Here it is desirable to measure both the transmit power and the power reflected by the antenna in the vicinity of the antenna in order to subsequently determine the actual matching of the antenna. This also increases the accuracy of the measurement, because the losses in the coaxial cable between the measuring device and the antenna, which increase with increasing frequency, simulate a better matching than it actually is.

In the concept described here, these measurements are carried out using a directional coupler, two power detectors and a WT32/ESP32 microcontroller. A web server runs on the microcontroller with the integrated Ethernet interface so that the results can be visualised on any browser in the network.
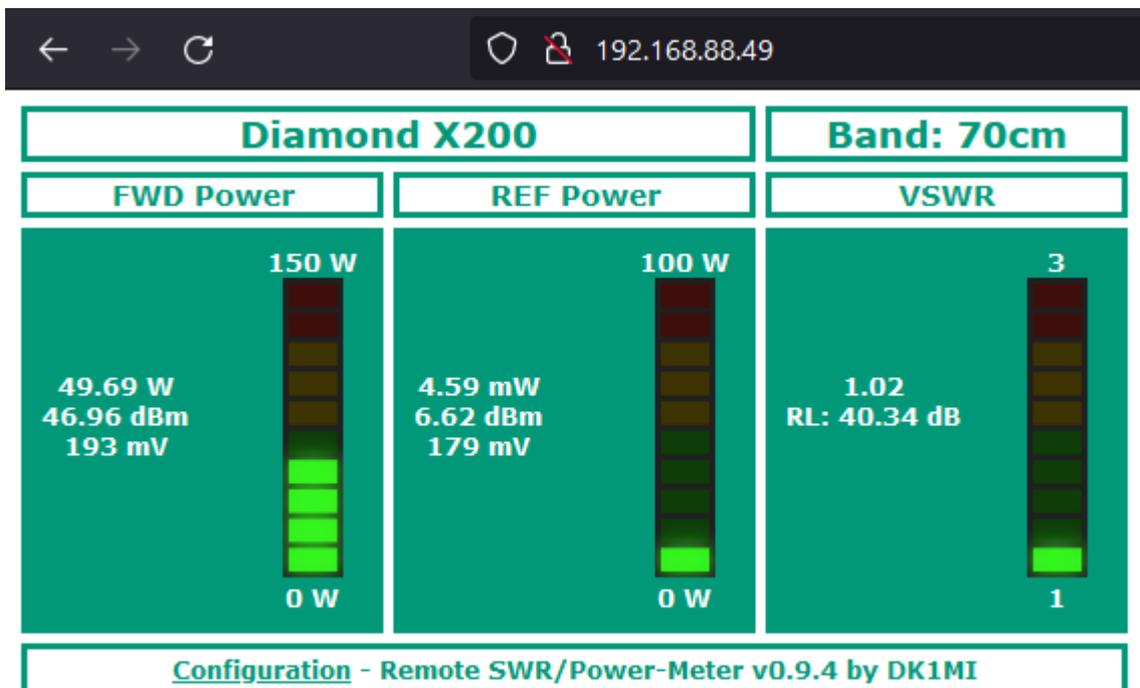
Figure 1: Dashboard of the web server

The aim was not to compete with commercial measuring devices, but to realise a cost-effective solution for an "operational measuring device" with sufficient accuracy.

Directional coupler

For the planned measurements, a directional coupler is required, which provides a small part of the forward and reflected power at 2 connections (FWD and REF).
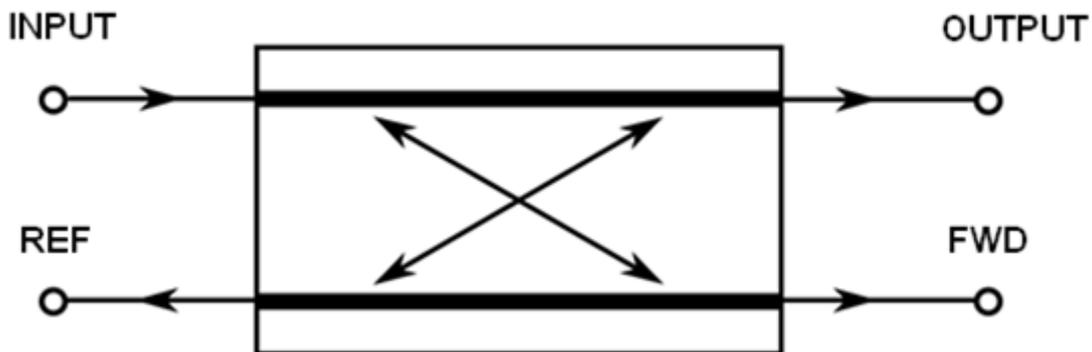
Figure 2: Principle of a directional coupler

A directional coupler has a frequency-dependent coupling factor in both forward FWD and reflected REF directions. These two coupling factors are not necessarily the same and are usually in the range between 10 dB and 40 dB.

The directivity describes which minimum return loss (for example from an antenna) can still be measured with the directional coupler. Ideally, with an optimally matched load connected to OUTPUT, no reflected power would be measured at REF. The directivity would then be infinite. Typically, it is between 20 and 40 dB. At a directivity of 25.4 dB, the minimum measurable VSWR is 1.11, at 30.9 dB only 1.06. The directivity is also frequency-dependent.

The insertion loss describes the ratio of the power at the OUTPUT to the INPUT or how much of the power fed into the directional coupler is lost. The losses are composed of the following parts:

- the losses due to reflection of part of the fed-in power at the input of the directional coupler due to its non-optimal matching to the transmitter (incl. the feed line)
- the attenuation within the directional coupler (e.g. due to dielectric losses)
- the losses due to the decoupling of part of the power via the measuring outputs FWD and REF (the greater the coupling factors, the smaller the influence on the insertion loss)

The insertion loss is also frequency-dependent. An insertion loss of 0.05 dB means that 1.2 % of the input power is lost. With an input power of 100 W, this would therefore be 1.2 W.

The quality of the measuring system is essentially determined by the directional coupler used, in particular by its directivity.

Detectors

The decoupled power can be detected by means of discrete diode detectors or an integrated logarithmic detector. Both types of detectors convert the power decoupled from the directional coupler into a DC voltage, which is then digitised by means of an AD converter. The microprocessor converts the detected DC voltages into RF power levels and also uses them to determine the matching (return loss) and the VSWR of the load connected to the OUTPUT.

Diode detectors

The characteristic curve of a diode detector is strongly non-linear in the lower range and then becomes more linear at higher levels. Here is an example:
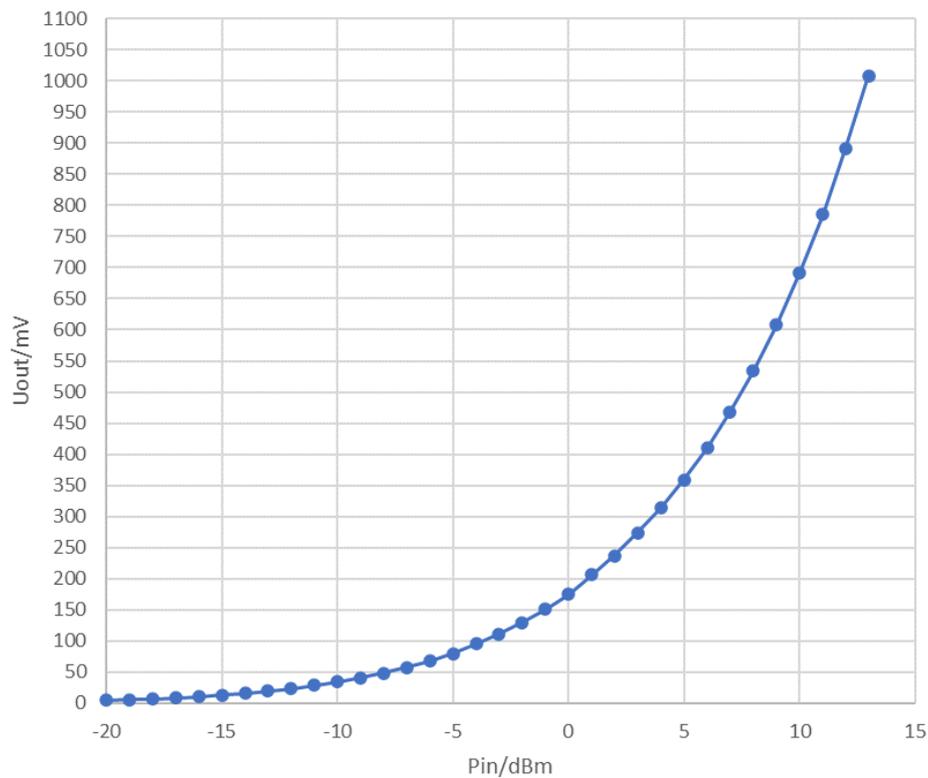
Figure 3: Characteristic curve of a diode detector

The characteristic curve is also temperature and frequency dependent. In the picture above you can quickly see the problem of diode detectors: At low powers to be measured, the output voltage is very small and the characteristic curve flat. This means that the DC output voltage changes very little as a function of the RF input power and the measurement error becomes large.

For the sake of completeness, it should be pointed out that there are diode detectors with negative or positive output voltages (see example above). Since the AD converters of simple microcontrollers can usually only measure positive voltages, in the case of a detector with a negative output voltage, an analogue inverter circuit with an operational amplifier is usually used to generate a voltage for the AD converter.

You can try to approximate the characteristic curve of the diode detector by means of a formula or store it in a lookup table in which the characteristic curve is reproduced by interpolation points for each frequency range.

Logarithmic detectors

Integrated logarithmic detectors are an alternative to diode detectors. These convert the RF input power (INPUT LEVEL in dBm) into a dB-linear DC output signal (V_{OUT} in V). In the following example, the frequency dependence of the characteristic curve can be clearly seen. The output characteristic is very linear over a wide input power range (>60 dB).
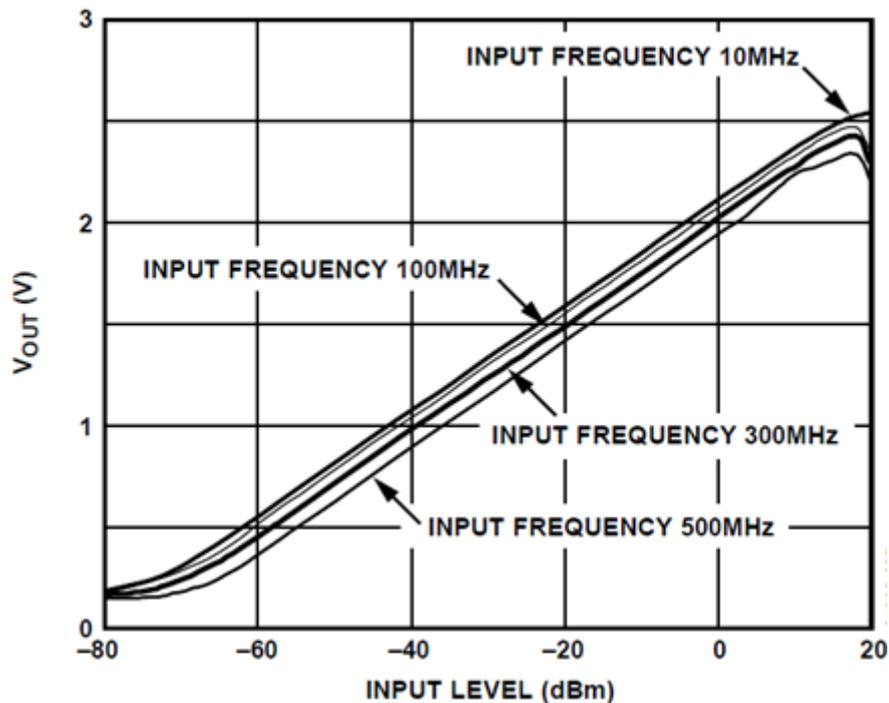
Figure 4: Characteristic curve of a logarithmic detector

Logarithmic detectors from Analog Devices are quite common. They are usually built into an 8-pin SMD housing and are easy to apply. The supply voltage range is usually 2.7 to 5.5 V.

You can buy quite cheap ready-made boards with such ICs from China. The following is an example:
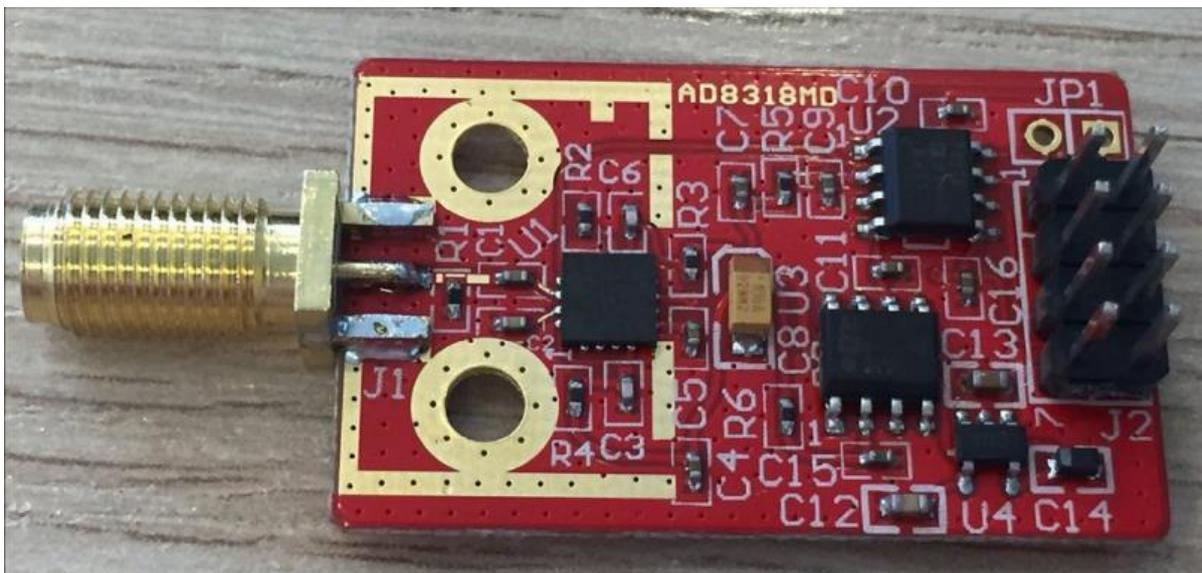
Figure 5: Example of a detector board with AD8318

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Implementation

Concept
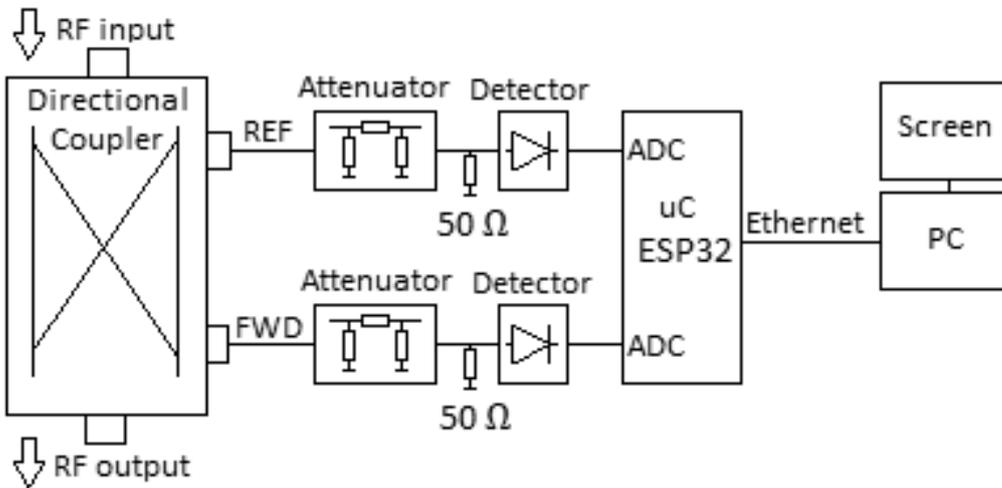
Figure 6: Block diagram of the set-up

The RF signals decoupled from the directional coupler are passed via attenuators to detectors. These convert the RF signals for forward FWD and reflected REF into DC voltages, which are then digitised by means of Analog-to-Digital converters (ADCs). The conversion of these DC voltages (mV) into corresponding RF powers (dBm) is done by means of calibration tables (lookup tables), which are stored in the microcontroller. Finally, the forward power and the reflected power can be converted from dBm to W:

$$P(W) = 1W \cdot \frac{10^{\frac{P(dBm)}{10}}}{1000} = 10^{\frac{P(dBm)-30}{10}}$$

The return loss in dB is the difference between the two values (forward FWD and reflected REF in dBm). We can also calculate the VSWR from the return loss in dB.

The calculated values are made available by means of a web server in order to display them on any end device with the help of a browser.

Hardware
The following hardware is required for this project:

- wt32-eth01 development board with integrated Ethernet interface
- USB-serial adapter (FTDI)
- Directional couplers and detectors that output a DC voltage (0 to 3.3 V) proportional to the forward and reflected power
- Calibrated power meter for the initial adjustment of the set-up

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Software / Libraries
- Arduino IDE
- Project code: https://codeberg.org/mclemens/wt32powermeter
- WebServer_WT32_ETH01 Library: https://github.com/khoih-prog/WebServer_WT32_ETH01

Installing the Arduino development environment and software
The following steps are required to compile and upload the code:

- Download and install the Arduino IDE 2.1: https://wiki-content.arduino.cc/en/software
- Follow these instructions to install the ESP32 board definitions:
  https://randomnerdtutorials.com/installing-esp32-arduino-ide-2-0/
- Select the correct board in the Arduino IDE: Tools → Board → esp32 → ESP32 Dev Module
- Install all required libraries: Tools → Manage Libraries → → Search for "WebServer_WT32_ETH01" → Install

Now download and install the required software:

- Download the code from the code wt32powermeter-respository:
  https://codeberg.org/mclemens/wt32powermeter/archive/main.zip
- Unpack the code to *C:\User\Documents\Arduino*:

	C:\Users\micha\Documents\Arduino\wt32pamon			˅	↻
	Name	Änderungsdatum	Typ		
	C index	04.05.2023 23:00	C Header-Quellda…		
	LICENSE	03.05.2023 21:19	Datei		
	README	03.05.2023 22:36	Markdown-Quelld…		
	wt32pamon	04.05.2023 22:47	INO-Datei		
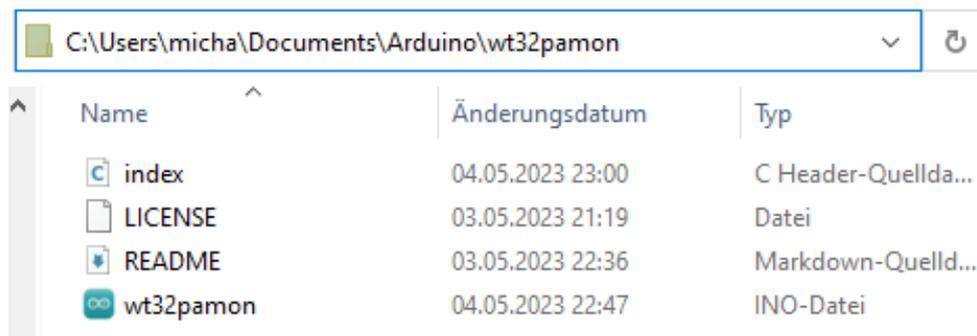
Figure 7: Unpacking the software

- Open the file *wt32powermeter.ino* within the Arduino IDE or double-click on the file.

Programming the board

The following steps are required to program the board:

- First connect the board to a USB-serial adapter according to the following illustration and connect the adapter to the PC via USB:
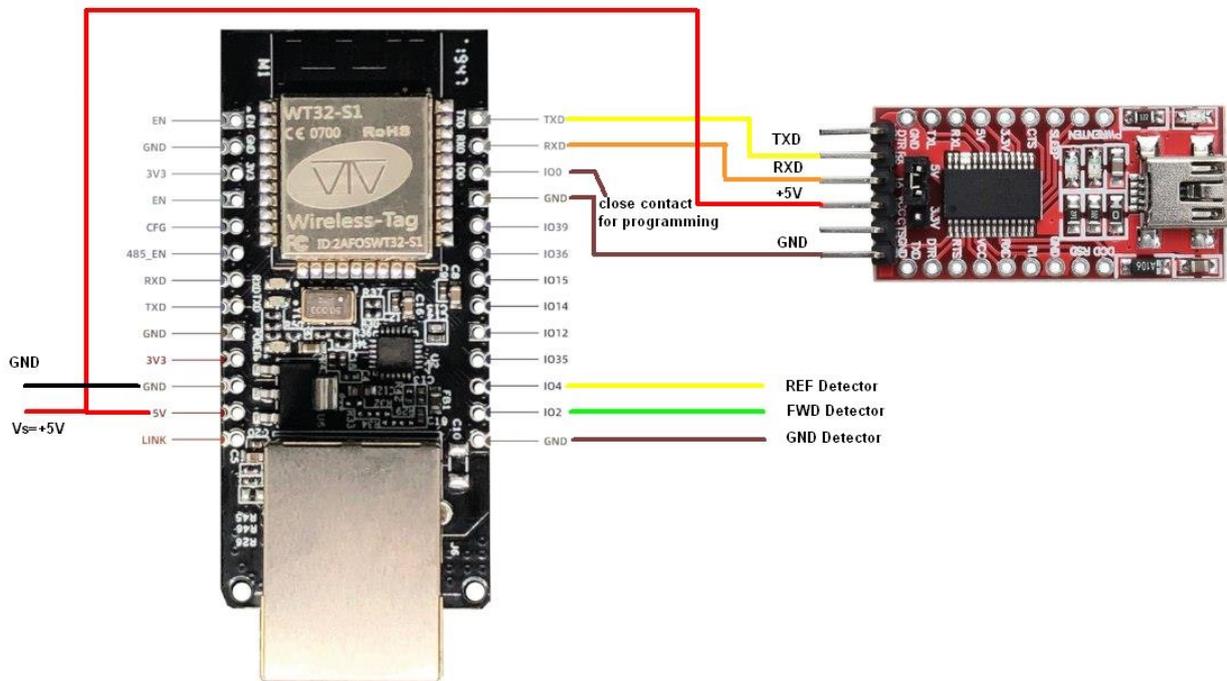
Figure 8: Connecting the programming adapter to the board

- Select the correct COM port in the Arduino IDE: Tools → Port → Select Port
- Select "ESP32 Dev Module" as the board:
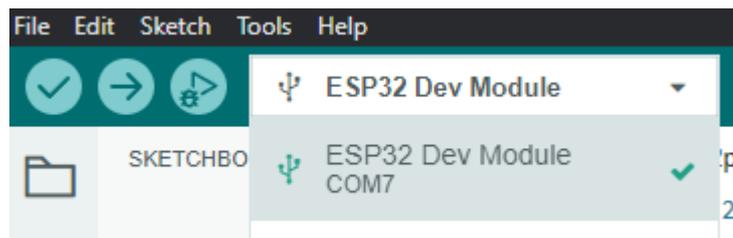
Figure 9: Selection of the ESP32 Development Module

- Click on "Upload" (upper left corner, arrow which points to the right)

During operation, the USB-serial adapter does not need to be connected. It is sufficient to apply supply voltage and ground and to connect the three pins IO2, IO4 and ground GND to the two detectors FWD and REF.

Please note that the two pins IO0 and GND only need to be bridged during programming. Do not forget to open the jumper again after programming.

Configuration

Please adapt the following code blocks in the file *wt32powermeter.ino* to your needs:

Network settings

```
ETH.begin(ETH_PHY_ADDR, ETH_PHY_POWER);
// Static IP, leave without this line to get IP via DHCP
//ETH.config(myIP, myGW, mySN, myDNS);
WT32_ETH01_waitForConnect();
```

By default, wt32powermeter is configured so that the microcontroller is assigned a dynamic IP address via DHCP. If this is desired, no action is required. If not, remove the two slashes at the beginning of the line *ETH.config(myIP, myGW, mySN, myDNS)* to get a static IP configuration. Please set the desired network configuration in the following part of the source code:

```
// Select the IP address according to your local network
IPAddress myIP(192.168.1.100);
IPAddress myGW(192.168.1.1);
IPAddress mySN(255.255.255.0);
IPAddress myDNS(192.168.1.1);
```

Definition of the frequency ranges

As explained before, the measurement setup shows a frequency-dependent behaviour. Therefore, the frequency ranges to be used can be defined in the software. To add or remove a band, adjustments are possible in the following part of the source code:

```
String band = "";
String default_band = "70cm";
String band_fwd = band + "_fwd";
String band_ref = band + "_ref";
String band_list[] = { "1.25cm", "3cm", "6cm", "9cm", "13cm", "23cm", "70cm", "2m",
"HF" };
```

Add or remove frequency bands to the variable *band_list[]* as required and set the desired default band with *default_band.*

Access to the web interface

Open your preferred browser and navigate to *http://<IP_ADDRESS>*, e.g. *http://192.168.1.100*.

The IP address is either the address you defined above or a dynamically assigned address. To find out the latter, you can log into your router and look for a dashboard that shows all currently connected network devices. Alternatively, you can activate the Arduino IDE's built-in serial monitor with the USB-to-serial adapter still plugged in. Every time the microcontroller is restarted, it outputs its current network configuration, among other things, via the serial interface.

Modern browsers often try to force a secure connection via HTTPS. This is not desired in this case. Make sure that *http://* and not *https://* is shown in the address line.

Configuration options in the browser

The first step is to configure the directional coupler incl. detector used by clicking on "Configuration" in the bottom left of the web server's dashboard (see Fig. 1). The following window will then open:

Configuration

Band: 70cm ⌄

Translation Detector Voltage /mV to RF-Power level /dBm

70cm FWD (mV:dBm)	70cm REF (mV:dBm)
70:50.20000	60:1.00000
590:49.20000	70:3.20000
640:42.20000	590:5.20000
760:42.20000	640:6.20000
880:42.20000	760:7.20000
1000:42.20000	880:7.70000
1130:42.20000	1000:8.20000
1250:42.20000	1130:9.20000
1380:42.20000	1250:12.20000
1500:42.20000	1380:14.20000
1610:2.20000	1500:2.20000
1730:16.20000	1610:2.20000
1850:11.20000	1730:1.20000
1970:6.20000	1850:1.20000
2000:4.20000	1970:6.20000
2040:1.20000	2000:4.20000
2300:1.20000	2040:1.20000
2500:1.00000	2041:1.22000
2600:0.89656	
2700:0.70000	

Save Calibration Data

General Configuration Items

Show voltage in mV (yes/no)	☑
Show power level in dBm (yes/no)	☑
Show power in Watt (yes/no)	☑
VSWR threshold that triggers a warning (e.g. 3)	2
Beep if VSWR threshold is exceeded (yes/no)	☐
Name of the antenna	Diamond X200
Max. FWD power displayed by LED bar graph in W (e.g. 100)	150
Max. REF power displayed by LED bar graph in W (e.g. 100)	100
Max. VSWR displayed by LED bar graph (e.g. 3)	3
Show LED graph for FWD power (yes/no)	☑
Show LED graph for REF power (yes/no)	☑
Show LED graph for VSWR (yes/no)	☑
Cable loss in db (e.g. 3)	3

Save Configuration

Back to Dashboard – Version: 0.9.4

Figure 10: Configuration window

<u>Maintenance of the calibration data</u>
First select the frequency band for which you want to enter the calibration data in the upper right dropdown box "Band".

The preset values of the calibration data are only exemplary and must be replaced by your own values for your individual setup. To do this, enter the mV:dBm value pairs for FWD and REF and click on "Save Calibration Data".

You can enter your data in any line, manual sorting of the value pairs is not necessary. After saving the data, it is automatically sorted and correctly displayed.

<u>General configuration elements</u>
The following general configuration options are available per frequency band:

Parameter	Function
Show voltage in mV (yes/no)	Activates or deactivates the display of the measured voltage
Show power level in dBm (yes/no)	Activates or deactivates the display of the measured power level in dBm
Show power in Watt (yes/no)	Activates or deactivates the display of the measured power in watts
VSWR threshold that triggers a warning (e.g. 3)	Any calculated value that exceeds the configured value results in a visual and optionally acoustic warning
Beep if VSWR threshold is exceeded (yes/no)	A beep sounds when the threshold set above is exceeded. (Does not work with all browsers)
Name of the antenna	Freely definable name of the antenna for this band
Max. FWD power displayed by LED bar graph in W (e.g. 100)	Sets the upper limit of the LED bar graph for the calculated FWD power
Max. REF power displayed by LED bar graph in W (e.g. 100)	Sets the upper limit of the LED bar graph for the calculated REF power
Max. VSWR displayed by LED bar graph (e.g. 3)	Sets the upper limit of the LED bar graph for the calculated VSWR
Show LED graph for FWD power (yes/no)	Activates or deactivates the LED bar graph for the FWD power.
Show LED graph for REF power (yes/no)	Activates or deactivates the LED bar graph for the REF power.
Show LED graph for VSWR (yes/no)	Activates or deactivates the LED bar graph for the VSWR.
Cable loss in dB (e.g. 3)	Sets the cable attenuation between the object of measurement and the Remote VSWR & Power Meter, which is taken into account in the calculations.

After you have made the desired changes, click on "Save Configuration".

Examples

Setup #1 ERICSSON directional coupler and AD8318 detectors

Setup #1 is based on a directional coupler from ERICSSON, 2 boards with AD8318 logarithmic detectors and a WT32-S1 uC module with integrated Ethernet interface.
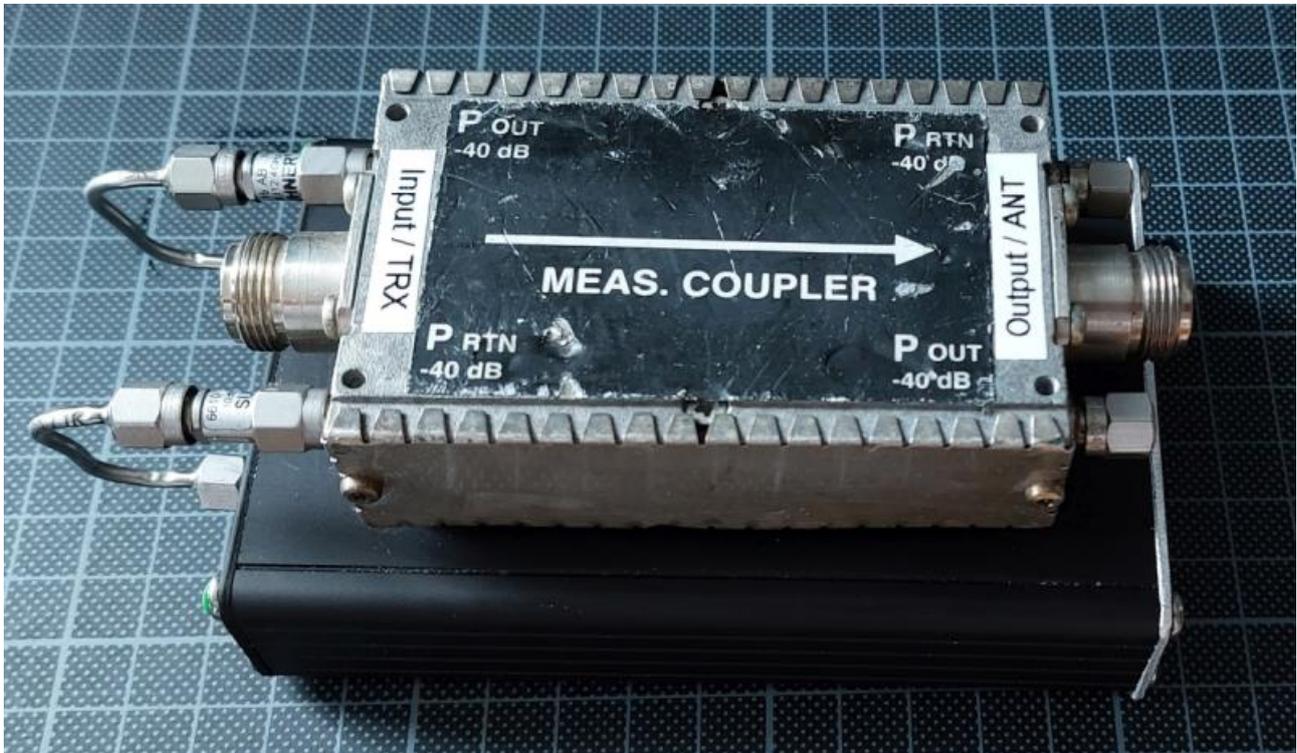
Figure 11: Set-up #1 with directional coupler from ERICSSON and detectors with AD8318

The directional coupler has frequency-dependent coupling attenuations D_{FWD} and D_{REF}. In addition to these values, the directivity DIR and the insertion loss IL are also listed in the following table.

Frequency /MHz	D_{FWD} /dB	D_{REF} /dB	DIR /dB	IL /dB
145	60,5	60,2	25,4	<0,05
435	51,2	51,0	26,8	<0,05
1296	42,3	42,5	38,1	<0,05
2400	38,6	38,7	30,9	<0,05

The AD8318 logarithmic detectors have a linear dynamic range from -57 dBm to +3 dBm. The dynamic range is therefore 60 dB. The frequency range covers 1 MHz to 8 GHz. The DC output voltage V_{OUT} decreases with increasing RF input level. The slope is -25 mV/dB. The characteristic curve differs depending on the frequency and is also temperature-dependent.
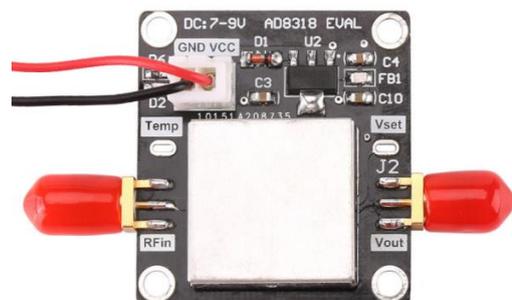
Figure 12: Detector board with shielded AD8318

However, the temperature dependence is only 0.5 dB, so that this can be neglected in a first approximation. The IC also provides a temperature-dependent reference voltage, which could be used to realise temperature-dependent compensation via software if required. However, this is not used here. By the way, the software can work with logarithmic detectors with positive or negative slope of the characteristic curve. Here is a typical characteristic curve of the AD8318.
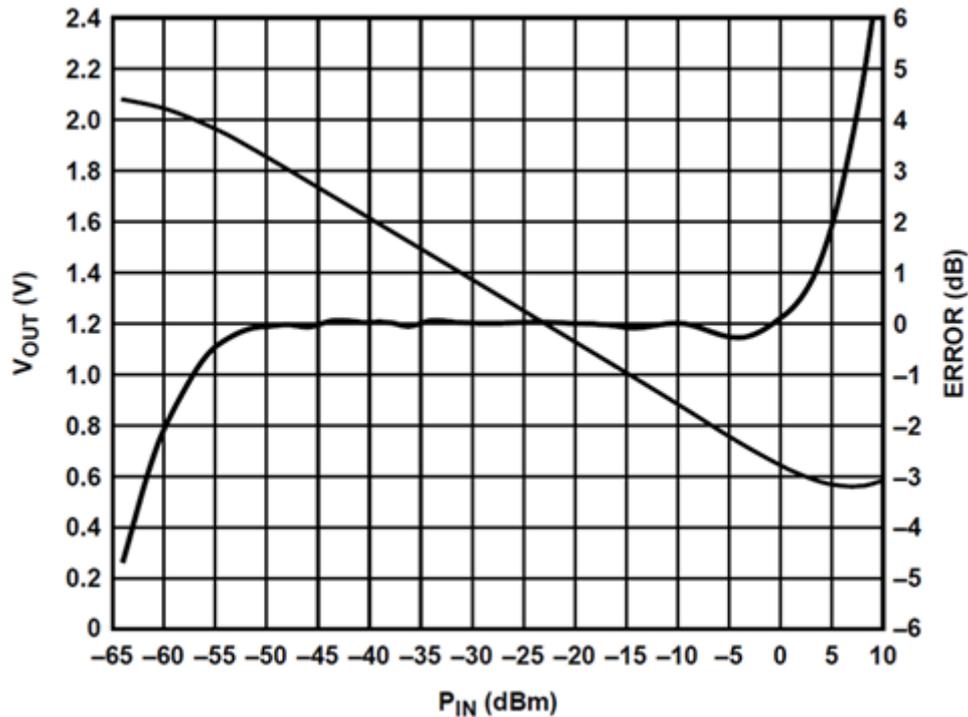
Figure 13: AD8318 typical characteristic at 5.8 GHz

With a transmit power of 14 W = 41.5 dBm and a coupling loss in the 13 cm band of 38.6 dB, the input level at the detector would be 3.1 dBm, i.e. at the upper limit of the AD8318's output range.

In order to be able to measure higher power levels, a 10 dB attenuator was inserted between the measuring outputs of the directional coupler and the inputs of the AD8318. This increases the maximum input level in the 13 cm band to 140 W.

Using the full dynamic range of the AD8318, the theoretical maximum and minimum input levels that can be measured with the ERICSSON directional coupler, including the 10 dB attenuators, are as follows:

Maximum input levels:

Frequenz /MHz	max. FWD-Power /dBm	max. FWD-Power /W	max. REF-Power /dBm	max. REF-Power /W
145	73,5	22400	73,2	20900
435	64,2	2600	64,0	2500
1296	55,2	330	55,5	350
2400	51,6	145	51,7	148

The maximum power for which the directional coupler is suitable has yet to be investigated. Unfortunately, a data sheet for this model is not available. Due to the low insertion loss and the high coupling attenuations, it is assumed that the setup is suitable for up to 500 W in the 2 m band and up

to 150 W in the 13 cm band. In the 2 m band, 100 W could already be measured without any problems, as will be shown later.

Minimum input levels:

Frequenz /MHz	min. FWD-Power /dBm	min. FWD-Power /mW	min. REF-Power /dBm	min. REF-Power /mW
145	13,5	22,4	13,2	20,9
435	4,2	2,6	4,0	2,5
1296	-4,8	0,33	-4,5	0,35
2400	-8,4	0,145	-8,3	0,148

If the frequency-dependent directivity of the directional coupler is taken into account and the full measurement accuracy of the directional coupler is to be utilised, the following minimum transmission levels result:

Frequenz /MHz	min. FWD-Power /dBm	min. FWD-Power /W
145	38,6	7,1
435	30,8	1,2
1296	33,6	2,3
2400	22,6	0,18

This means: If the transmit level in the 13 cm band is less than 0.18 W, the forward power is measured correctly (up to 0.145 mW), but the reflected power would no longer be detected with a very well-matched antenna (with a return loss of better than 30.9 dB). Thus the VSWR measurement is no longer correct, the VSWR is displayed worse than it actually is.
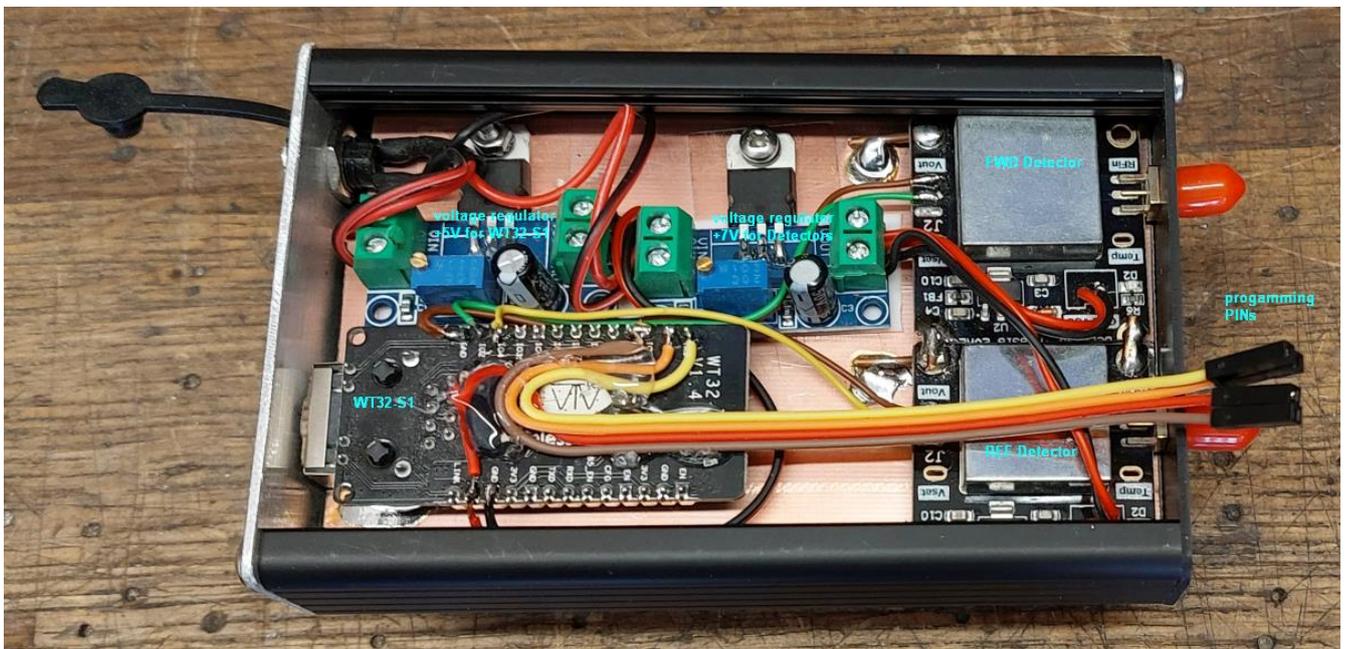
Figure 14: Interior view of the setup with ESP32 board, 2 detector boards and 2 voltage regulators
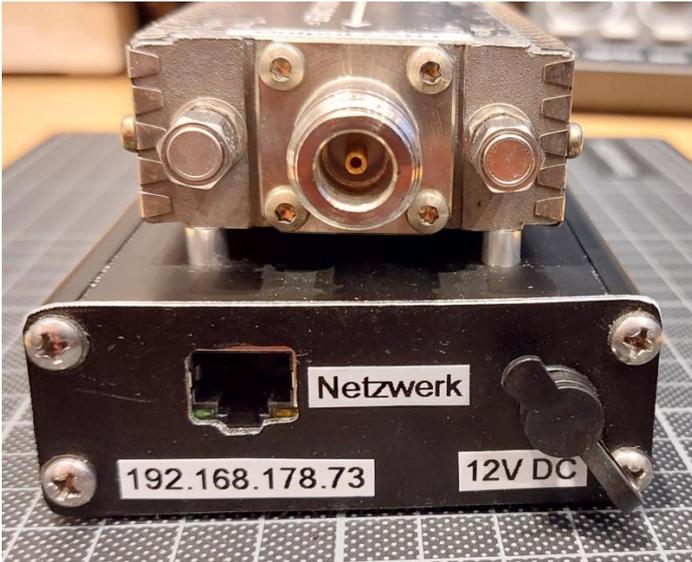
Figure 15: Front of the Remote VSWR & Power Meter

Figure 16: Back of the Remote VSWR & Power Meter

The following is an example of the characteristic curve of the setup measured at 145 MHz. The maximum power of 50 dBm (100 W) was limited by the output power of the transmitter used.
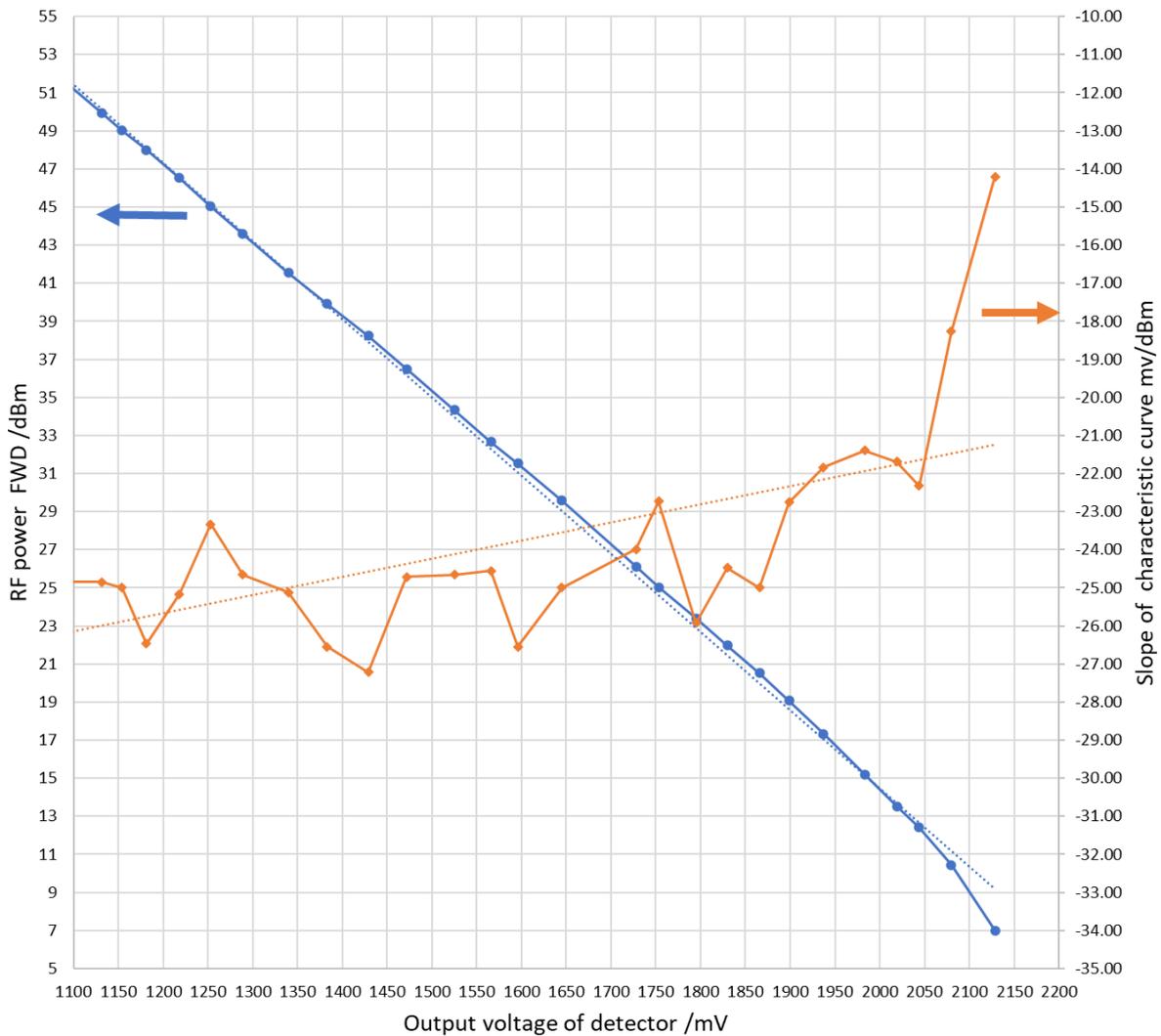
Figure 17: Output characteristic of the detector as a function of the RF power at the input of the directional coupler

Setup #2 NARDA 31119 directional coupler and AD8313 detectors

In the second set-up, a directional coupler from NARDA with the type designation 31119 is used. According to the imprint, this directional coupler was obviously used by Motorola in base stations.

Figure 18: Directional coupler NARDA 31119
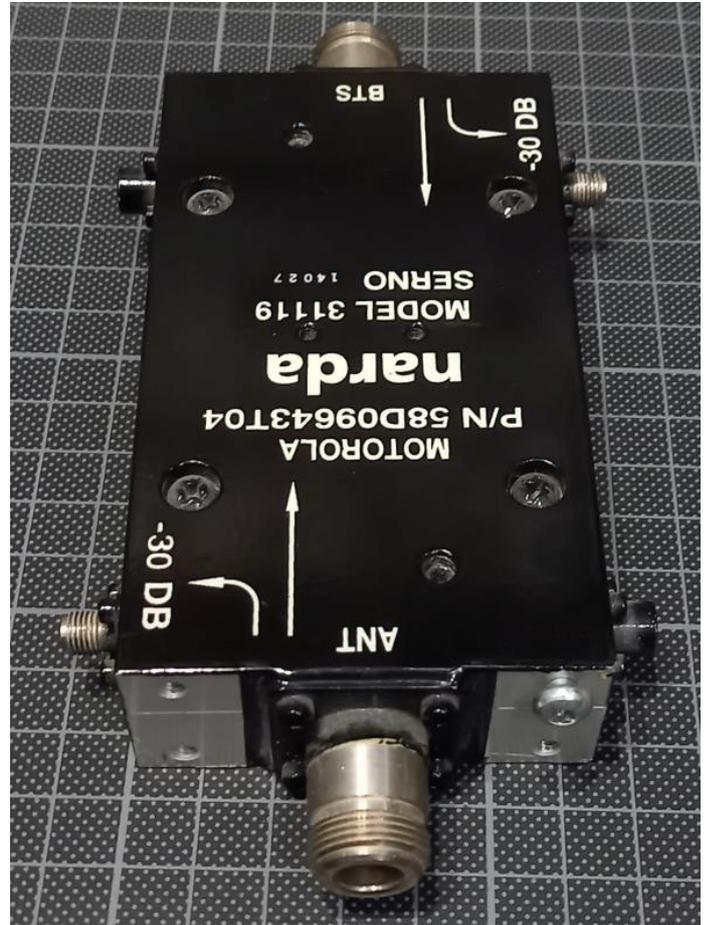
Figure 19: Directional coupler NARDA 31119

This time, logarithmic detectors of the type AD8313 are used. Corresponding ready-built boards can also be found cheaply at online retailers.

Figure 20: Detector board with AD8313

The AD8313 has a linear dynamic range from -75 dBm to -5 dBm. The dynamic range is therefore 70 dB. The frequency range covers 100 MHz to 2.5 GHz.

With the AD8313, the DC output voltage increases with increasing RF input level. The DC output voltage range of 0.5 V to 1.75 V is slightly smaller than that of the AD8313.
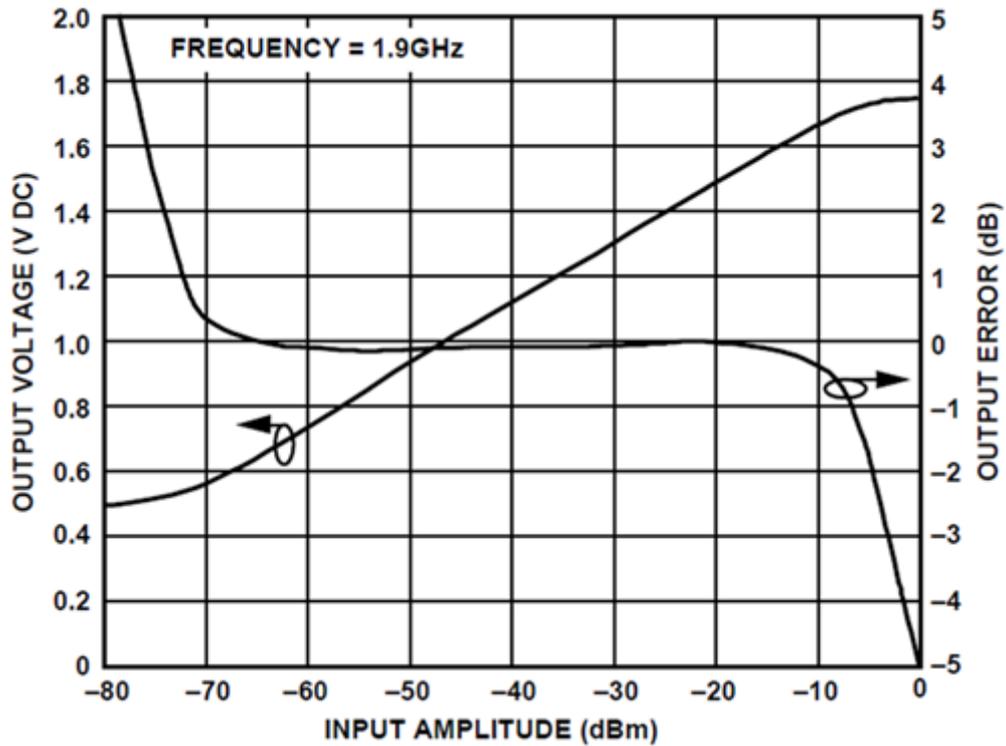
Figure 21: AD8313 typical characteristic at 1.9 GHz

By the way, the characteristic curves of this cheaper detector show a somewhat higher dependence on frequency and temperature. However, these are still sufficient for our purposes.
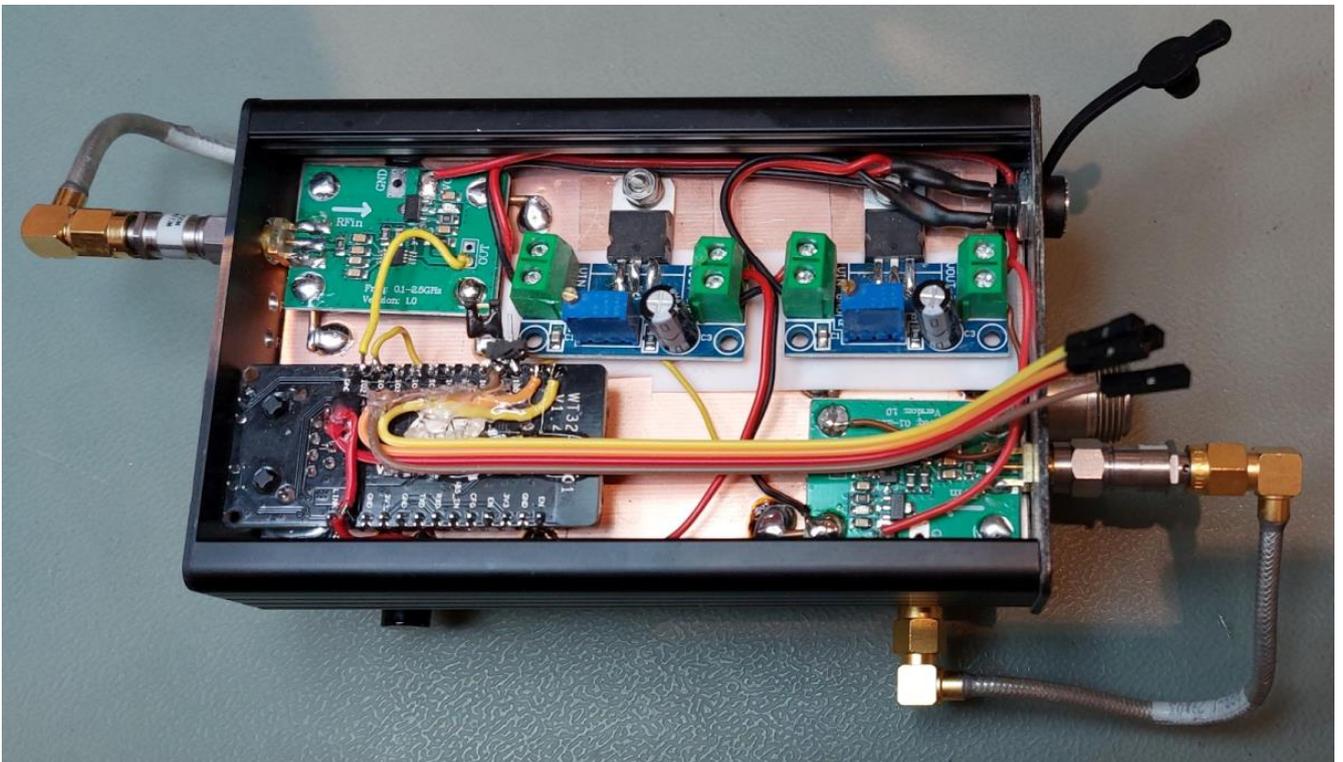
Figure 22: Interior view of the setup with AD8313 boards

This is an example of the calibration data for the Remote VSWR & Power Meter in the 70 cm band:

Configuration

Band Selection

70cm ⌄

Translation Detector voltage /mV to RF-Power level /dBm

FWD

millivolt (mV)	decibel-milliwatts (dBm)	Watt	Action
594	-7.000	0.00020	delete
602	-4.600	0.00035	delete
620	-1.600	0.00069	delete
650	0.000	0.00100	delete
663	1.800	0.00151	delete
672	3.000	0.00200	delete
709	5.200	0.00331	delete
740	7.000	0.00501	delete
784	9.000	0.00794	delete
801	10.000	0.01000	delete
857	13.000	0.01995	delete
891	14.800	0.03020	delete
915	16.000	0.03981	delete
957	18.300	0.06761	delete
1117	23.000	0.19953	delete
1145	24.800	0.30200	delete
1185	27.800	0.60256	delete
1210	29.000	0.79433	delete
1262	32.600	1.81970	delete
1297	34.800	3.01995	delete
1328	36.500	4.46684	delete
1373	38.500	7.07946	delete
1401	40.000	10.00000	delete
1433	41.900	15.48817	delete
1458	43.000	19.95262	delete
1490	44.800	30.19951	delete
1502	45.400	34.67370	delete
1533	47.000	50.11872	delete
1550	48.100	64.56540	delete
			add/edit

REF

millivolt (mV)	decibel-milliwatts (dBm)	Watt	Action
596	-7.000	0.00020	delete
600	-4.600	0.00035	delete
620	-1.600	0.00069	delete
629	-0.200	0.00095	delete
664	3.000	0.00200	delete
685	4.300	0.00269	delete
717	6.200	0.00417	delete
729	7.000	0.00501	delete
771	9.000	0.00794	delete
820	11.800	0.01514	delete
847	13.000	0.01995	delete
894	15.400	0.03467	delete
918	17.000	0.05012	delete
942	18.300	0.06761	delete
1104	23.000	0.19953	delete
1134	24.800	0.30200	delete
1173	27.300	0.53703	delete
1197	29.300	0.85114	delete
1231	31.600	1.44544	delete
1268	34.000	2.51189	delete
1303	36.000	3.98107	delete
1332	38.500	7.07946	delete
1368	40.000	10.00000	delete
1404	41.800	15.13561	delete
1433	43.100	20.41737	delete
1466	44.800	30.19951	delete
1480	45.400	34.67370	delete
1502	46.500	44.66836	delete
1509	47.000	50.11872	delete
1530	48.100	64.56540	delete
			add/edit

Figure 23: Example of calibration data table in the 70 cm band

Structure #3 Directional coupler from an old VSWR meter with integrated detector diodes

The basis of this setup is an old VSWR / power meter for short wave, from which the directional coupler with integrated detector diodes was removed and used.

Fig. 24: Old VSWR / power meter for short wave

Figure 25: A directional coupler with integrated detector diodes is found in the VSWR meter

After removing the directional coupler, the open side was covered with copper foil to ensure proper shielding.

Figure 26: Disassembled directional coupler with additional shielding

The directional coupler fits perfectly into Michael's favourite 5-Euro project box
(Donau Elektronik - KGB15 Euro Box small, Blue, 95x135x45).
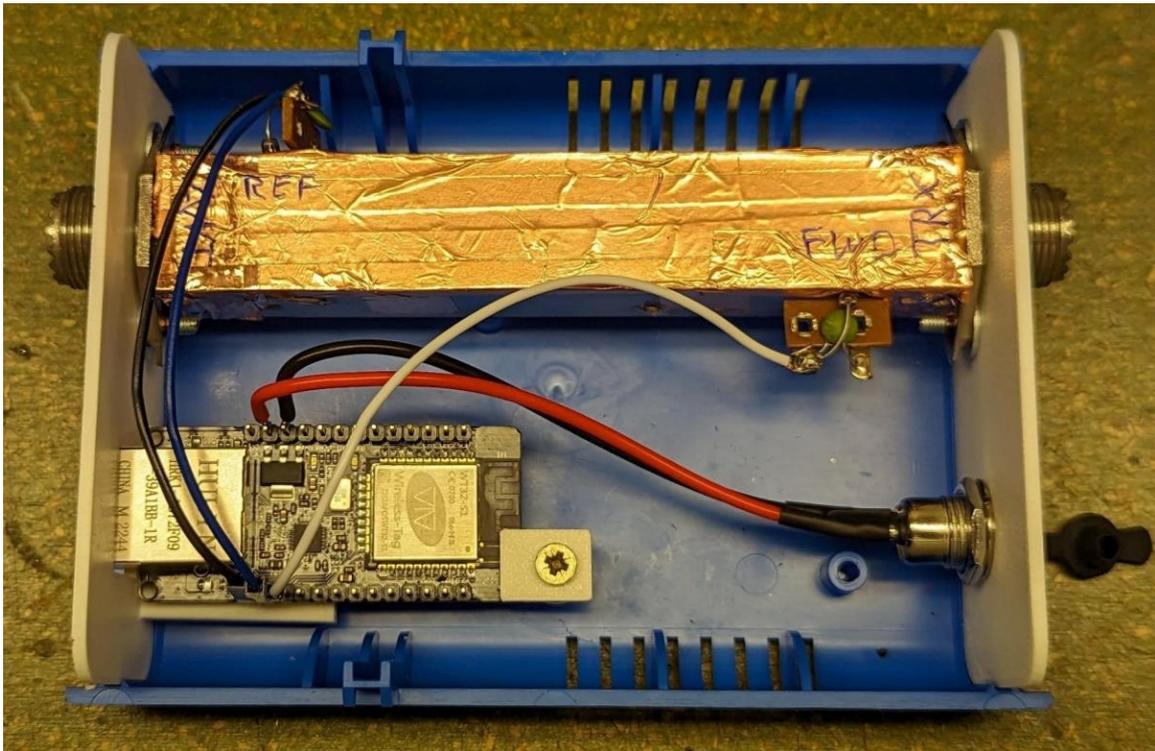
Figure 27: Directional coupler and microcontroller board in the housing
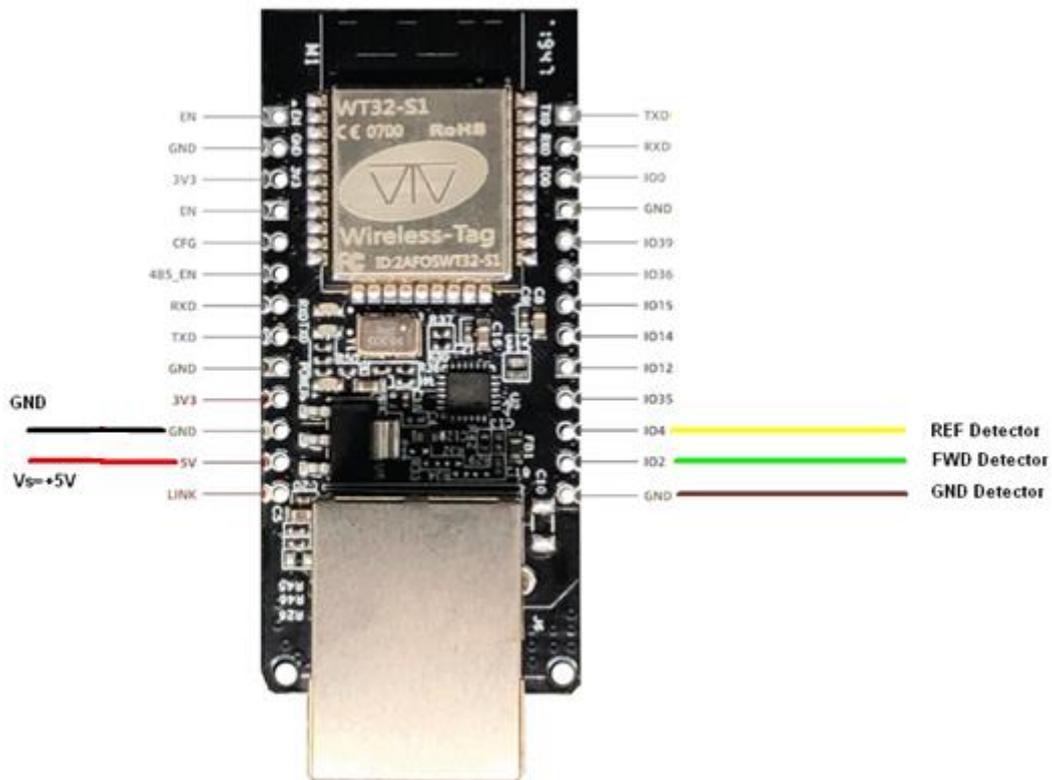
Figure 28: Wiring diagram microcontroller board

Figure 29: Front panel and rear panel were produced using 3D printing

The calibration will be explained again using this setup as an example:

1. Connect the components as follows: Transceiver-> Remote VSWR & Power Meter -> Known Power Meter -> Dummy Load
2. Set the transceiver to the desired band, operating mode FM
3. Set power to 1 W, press PTT, read the measured power at the known power meter and the measured voltage of the Remote VSWR & Power Meter and enter it in a calibration table. This table refers to FWD.
4. Repeat step 3 while gradually increasing the transmitting power until the maximum power is reached.
5. Remove the Remote VSWR & Power Meter from the set-up and insert it back into the unit chain the other way round.
6. Repeat steps 3 and 4 to generate another table REF.
7. Calculate the dBm values for each measured power in the tables:

$$P_{(dBm)} = 10 \cdot \log_{10}(1000 \cdot P_{(W)} / 1W)$$

8. Now you should have two tables with pairs of values in the format mV:dBm.

9. Paste both tables into the configuration page of the Remote VSWR & Power Meter. If you have the tables available electronically, e.g. in Excel, this is particularly easy to do by copy & paste.

Summary

A solution for a remote VSWR & Power Meter was presented. Due to the universal Ethernet interface and the integrated web server, the measuring unit can be configured and read out from any device using a browser.

The concept supports any directional couplers and detectors and therefore offers an ideal experimental platform from shortwave to the GHz range.

This and further information can be found here:

https://dk1mi.radio/remote-power-meter/

https://www.dd1us.de

The current version of the software can be found in source code here:
https://codeberg.org/mclemens/wt32powermeter/