Description:	This document describes the design of the RF SplitBox.
Title:	**Critical Design Review of the RF SplitBox**

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1 Introduction

1.1 Overview of the RF SplitBox

The RF SplitBox is a device distributing the RF signals coming from a high power amplifier and an accelerating cavity. These signals are split and fed the LLRF Control System and the Interlock System.

The device also includes the distribution circuit for the RF Reference signal and a low-pass filter for the RF drive signal.

1.2 Block diagram

The block diagram of the RF SplitBox is presented in Figure 1.

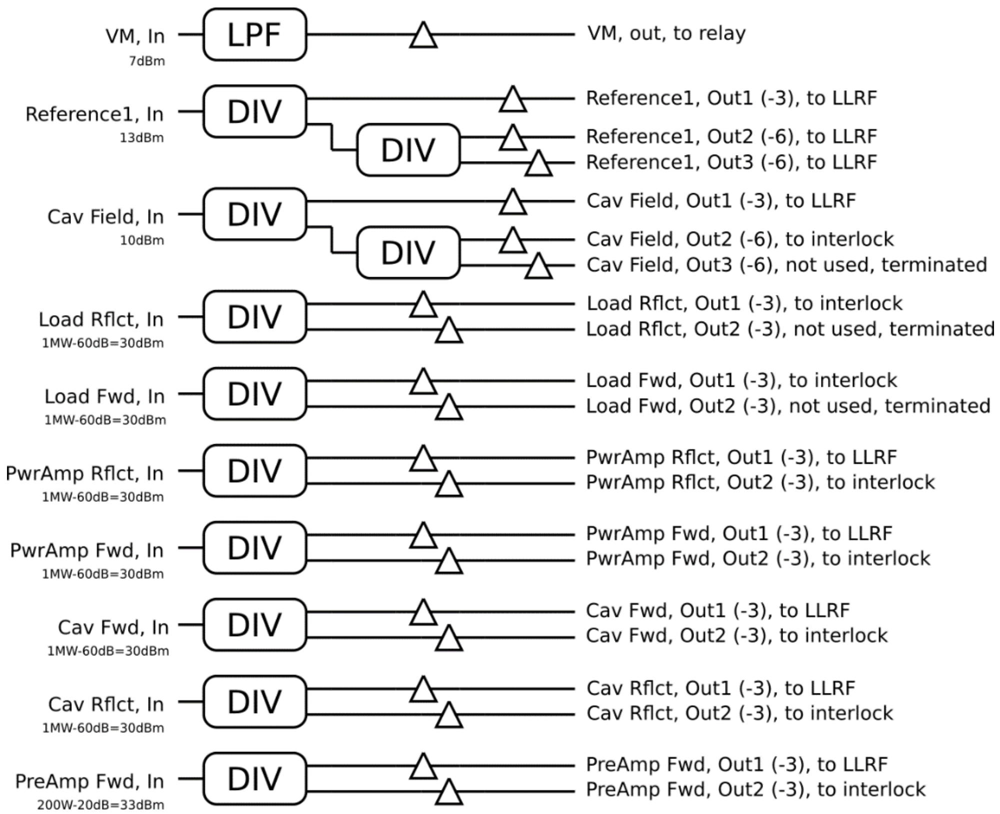

Figure 1. Block diagram of the RF SplitBox.

1.3 Requirements

Technical requirements for RF SplitBox devices are listed in Tables 1 to 4.

Table 1. Requirements for analog inputs.

Name	Connector Type	Maximum Power Level [dBm]
VM In	SMA (50 Ω)	Max. 20
Reference In	SMA (50 Ω)	Max. 30
Cavity Field In	SMA (50 Ω)	Max. 30
Load Reflected In	SMA (50 Ω)	Max. 30
Load Forward In	SMA (50 Ω)	Max. 30
PwrAmp Reflected In	SMA (50 Ω)	Max. 30
PwrAmp Forward In	SMA (50 Ω)	Max. 30
Cavity Forward In	SMA (50 Ω)	Max. 30
Cavity Reflected In	SMA (50 Ω)	Max. 30
PreAmplifier Forward In	SMA (50 Ω)	Max. 30

Table 2. Requirements for analog outputs.

Name	Connector Type
VM out	SMA (50 Ω)
Reference Out 1	SMA (50 Ω)
Reference Out 2	SMA (50 Ω)
Reference Out 3	SMA (50 Ω)
Cav Field Out 1	SMA (50 Ω)
Cav Field Out 2	SMA (50 Ω)
Cav Field Out 3	SMA (50 Ω)
Load Reflected Out 1	SMA (50 Ω)
Load Reflected Out 2	SMA (50 Ω)
Load Forward Out 1	SMA (50 Ω)
Load Forward Out 2	SMA (50 Ω)
PwrAmp Reflected Out 1	SMA (50 Ω)
PwrAmp Reflected Out 2	SMA (50 Ω)
PwrAmp Forward Out 1	SMA (50 Ω)
PwrAmp Forward Out 2	SMA (50 Ω)
Cavity Forward Out 1	SMA (50 Ω)
Cavity Forward Out 2	SMA (50 Ω)
Cavity Reflected Out 1	SMA (50 Ω)
Cavity Reflected Out 2	SMA (50 Ω)
Preamplifier Forward Out 1	SMA (50 Ω)
Preamplifier Forward Out 2	SMA (50 Ω)

Table 3. Other requirements.

Name	**Value**
Signal Frequency (F_0)	352.21 MHz or 704.42 MHz (2 variants)
Maximum Insertion Loss (VM In to VM out)[1,2]	2 dB
Maximum Insertion Loss (Reference In to Reference Out 1)[1,2]	4 dB
Maximum Insertion Loss (Reference In to Reference Out 2 and 3)[1,2]	8 dB
Maximum Insertion Loss (Cavity Field In to Cavity Field Out 1)[1,2]	8 dB
Maximum Insertion Loss (other)[1,2]	4 dB
Input Return Loss	10 dB
Output Return Loss	10 dB
Maximum phase drift between paths: • Cavity Field In to Cavity Field Out 1 • Reference In to Reference Out 2	0.02° change from 22 to 27°C
Isolation (Common Inputs)	10 dB
Isolation (Different Inputs)	75 dB
Chassis	1U 19'' rack mount metal enclosure
Operating Temperature	0 to 80°C
Storage Temperature	-20 to 80°C

[1]Measured at F_0.
[2]Without the attenuator.

Table 4. Requirements for VM Filter.

Frequency	VM Filter Attenuation
2 x F_0	> 35 dB
3 x F_0	> 40 dB
4 x F_0	> 40 dB
5 x F_0	> 40 dB
6 x F_0	> 30 dB

2 Modules design

Given the architecture shown in figure 1, the RF SplitBox design was split into three types of modules:

- SplitBox Low Pass Filter – 2 variants, for 352.21 MHz and 704.42 MHz,
- SplitBox 3-WayDivider,
- SplitBox 2-WayDivider.

Each RF SplitBox device will consist of 10 such modules: one Low Pass Filter, two 3-WayDividers and seven 2-WayDividers.

2.1 Low Pass Filter

SplitBox Low Pass Filter module (LPF for short) part of block diagram is shown in Figure 2.

Figure 2. Block diagram of Low Pass Filter module.

Appropriate Mini-Circuits' LFCN-series ceramic filters were chosen for both variants of SplitBox LPF module. For the 352.21 MHz variant a LFCN-320+ chip was chosen, and for the 704.42 MHz variant – LFCN-630+. Both of these have an insertion loss less than required 2 dB at their F_0. Attenuation values listed in datasheets [1, 2] for both filters were compared with requirements in Table 5.

Table 5. Comparison of filter attenuation values.

Frequency	Attenuation required	LFCN-320 (F_0 = 352.21 MHz)	LFCN-630+ (F_0 = 704.42 MHz)
F_0	< 2 dB	~ 1 dB	~ 1 dB
2 x F_0	> 35 dB	~ 40 dB	~ 48 dB
3 x F_0	> 40 dB	~ 45 dB	~ 72 dB
4 x F_0	> 40 dB	~ 45 dB	~ 51 dB
5 x F_0	> 40 dB	~ 55 dB	~ 44 dB
6 x F_0	> 30 dB	~ 72 dB	~ 36 dB

A printed circuit board was designed for the RF SplitBox LPF module. It consists of a LFCN filter, optional attenuators and SMA connectors. Its 3D model is presented in Figure 3.

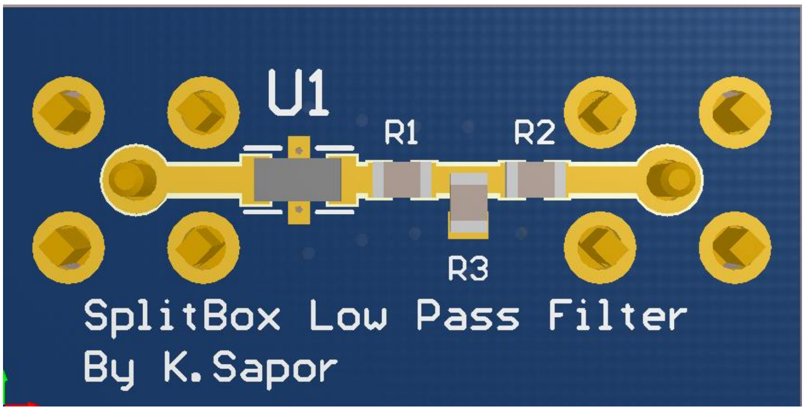

Figure 3. 3D model of RF SplitBox Low Pass Filter PCB.

2.2 3-Way Divider

SplitBox 3-Way Divider module part of block diagram is shown in figure 4.

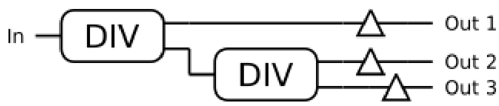

Figure 4. Block diagram of 3-Way Divider module.

This module will be used to distribute Reference and Cavity Field signals to the LLRF and Interlock systems.

Mini-Circuits' GP2S1+ power splitter was chosen for both types of divider modules. According to its datasheet [3], it satisfies the requirements of Internal Loss and Return Loss listed in the table 3. Additionally, using the scattering matrix data for different temperatures and frequencies, provided by Mini-Circuits [4], authors were able to check that this power splitter should also meet the phase drift requirement.

A printed circuit board was designed for the RF SplitBox 3-Way module. It consists of: two GP2S1+ power splitters, optional attenuators, an optional matching circuit and SMA connectors. Its 3D model is presented in Figure 5.

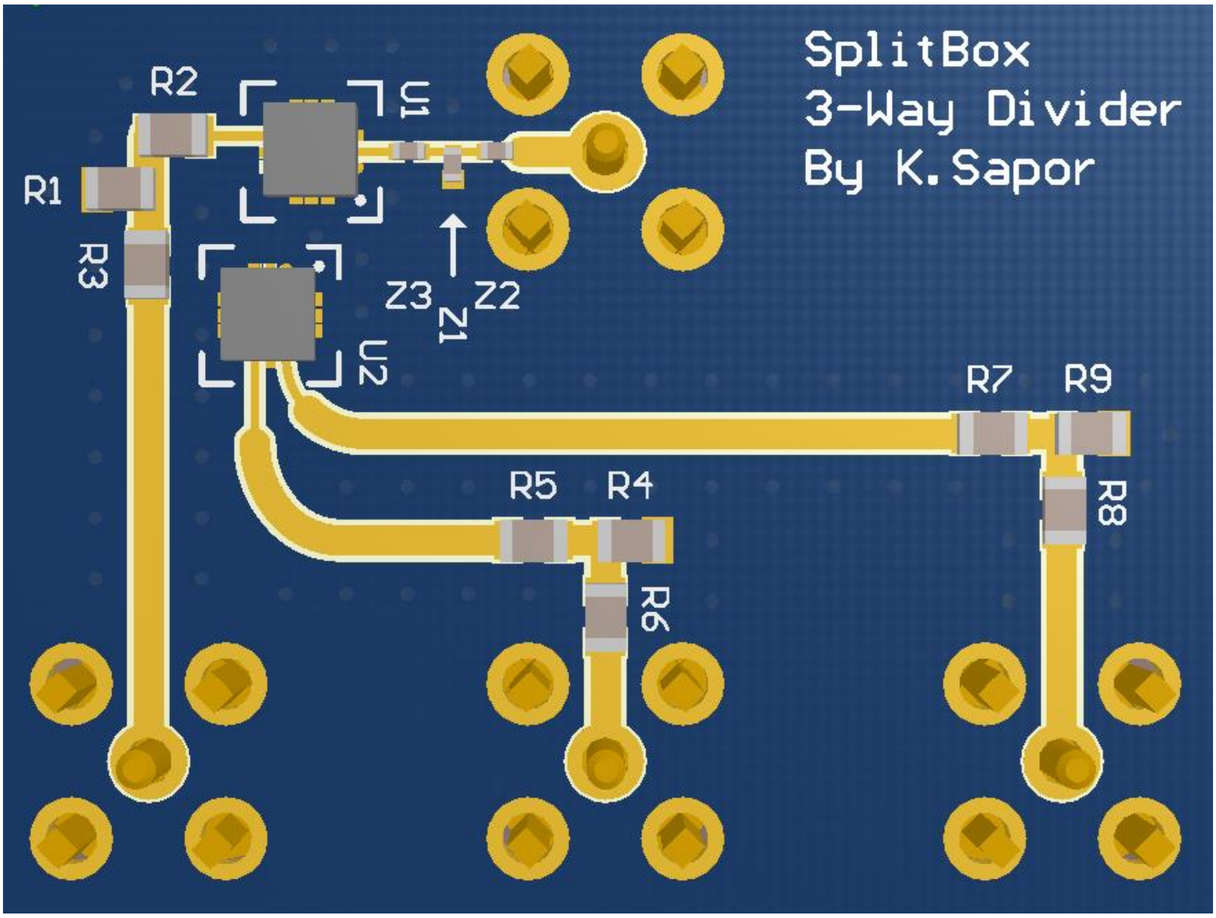

Figure 5. 3D model of RF SplitBox 3-Way Divider PCB.

2.3 2-Way Divider

The block diagram of the SplitBox 2-Way Divider is shown in Figure 6.

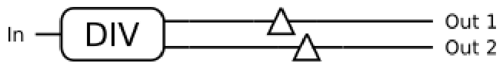

Figure 6. Block diagram of 2-Way Divider module.

This module will be used to distribute load, power amplifier, cavity and preamplifier signals to the LLRF and Interlock systems. It has the same components as the 3-Way Divider module.

A printed circuit board has been designed for the RF SplitBox 2-Way module. It consists of: GP2S1+ power splitter, optional attenuators, optional matching circuit and SMA connectors. Its 3D model is presented in Figure 7.

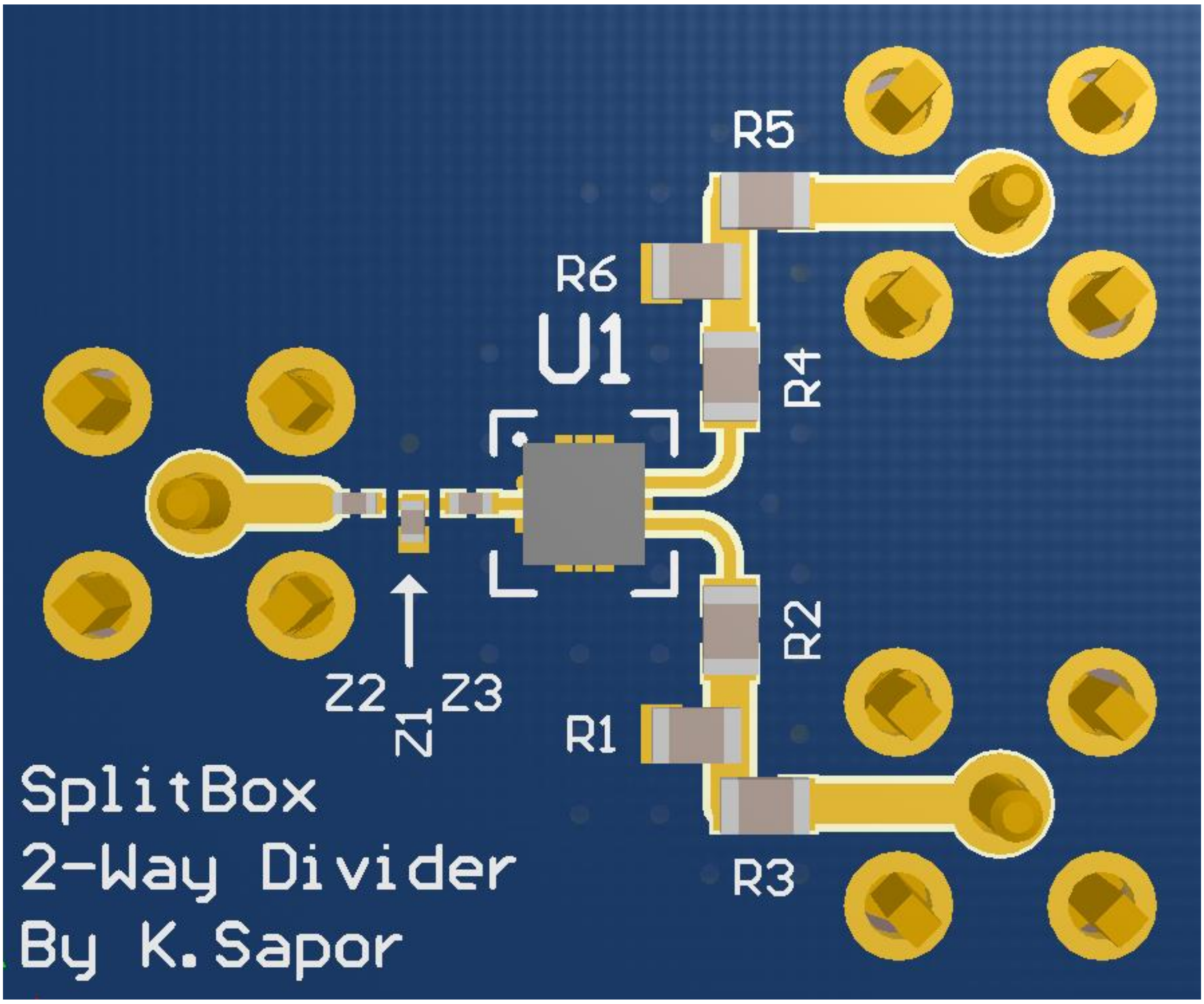

Figure 7. 3D model of RF SplitBox 2-Way Divider PCB.

3 Phase drift measurements

To check if the splitters will meet the phase drift requirement, a test board with two GP2S1+ splitters was designed and assembled. Its photo is shown in figure 8. The results of performed measurements are described in this section.

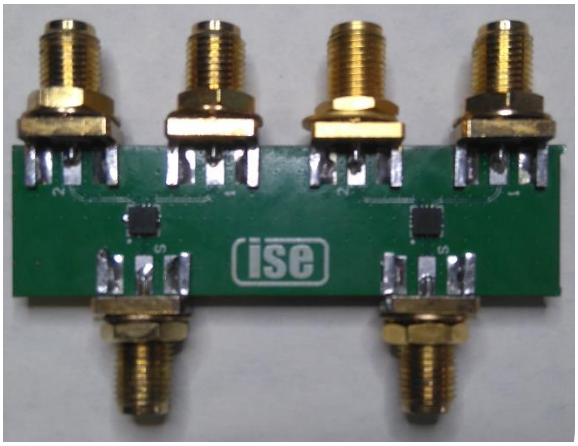

Figure 8. A photo of the test board with two GP2S1+ splitters.

3.1 Phase drift between outputs of a single splitter

First measurement determined the phase drift between outputs of a single GP2S1+ splitter. The block diagram presented in Figure 8 shows the structure of the measurement setup.

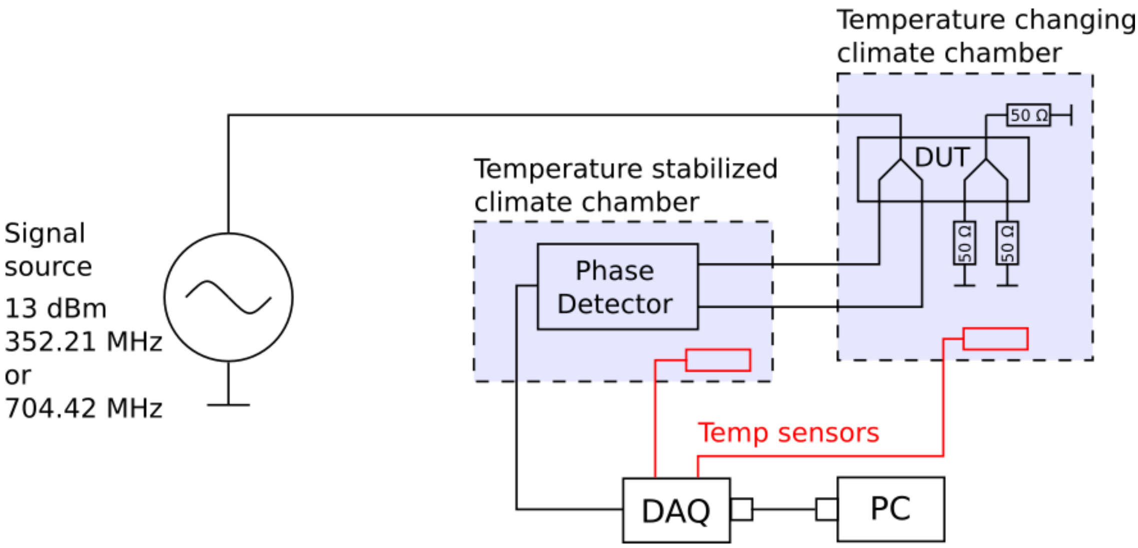

Figure 9. Setup used for a single splitter phase drift measurement.

During the measurement the phase detector was placed in the climate chamber with stable temperature of 25°C (± 0.5°C). The test board (DUT In Figure 9) with two GP2S1+ power splitters was placed in a second climate chamber. The temperature inside this chamber was swept in the 10°C-50°C range.

The outputs of one of the splitters were connected to the phase detector inputs with cables of the same type and length to minimize their contribution to the phase drift measured. All ports of the other splitter were terminated with 50 Ω loads. A pair of thermocouples was used to measure temperature changes in both climate chambers.

One measurement lasted for 15 hours and it was done twice – one for a 704.42 MHz signal and the other for 352.21 MHz signal. The results of the first measurement are presented nn Figures 10 and 11. The results of the second one are presented in Figures 12 and 13.

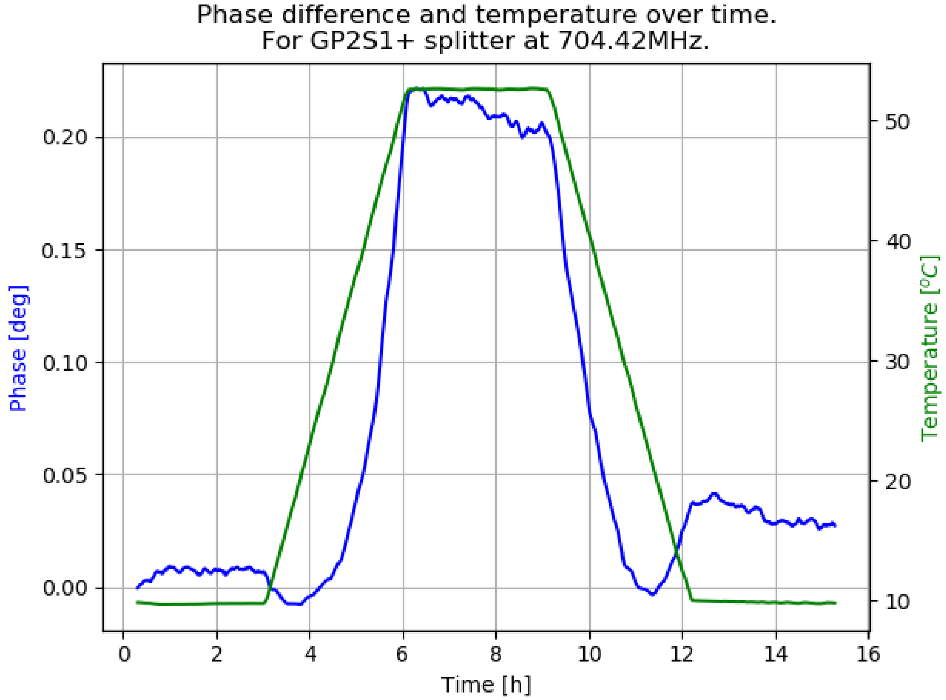

Figure 10. Phase difference between outputs of a single splitter and temperature over time (704.42 MHz).

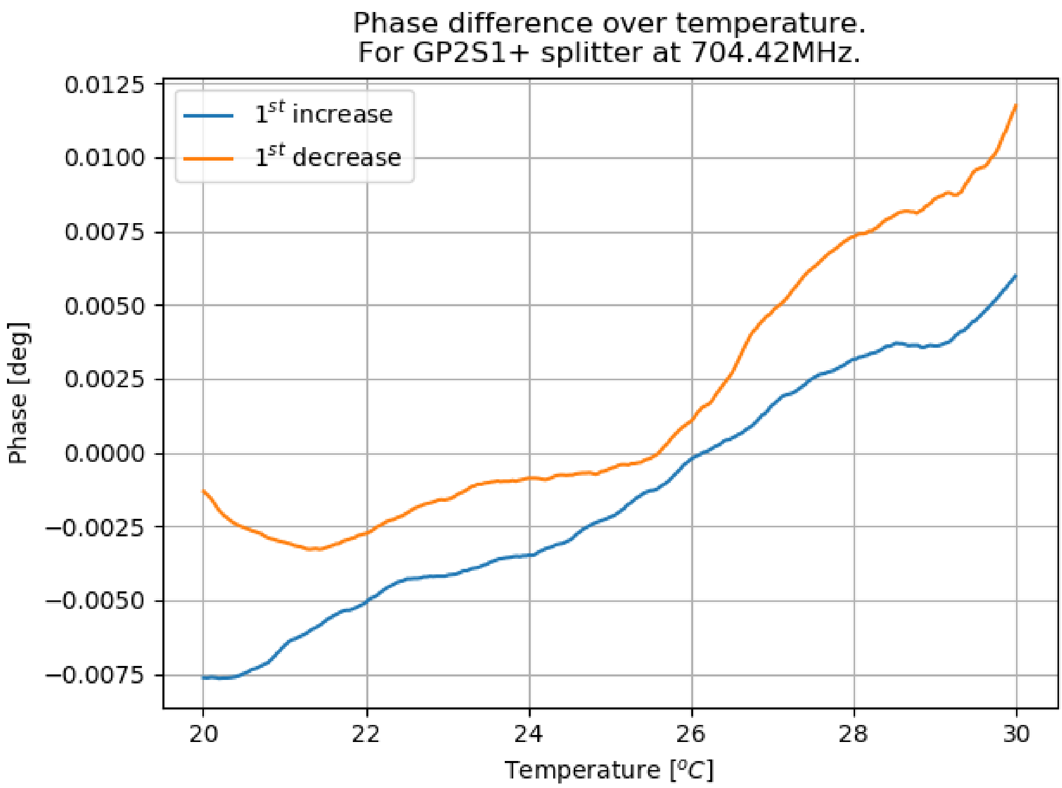

Figure 11. Phase difference between outputs of a single splitter over temperature (704.42 MHz).

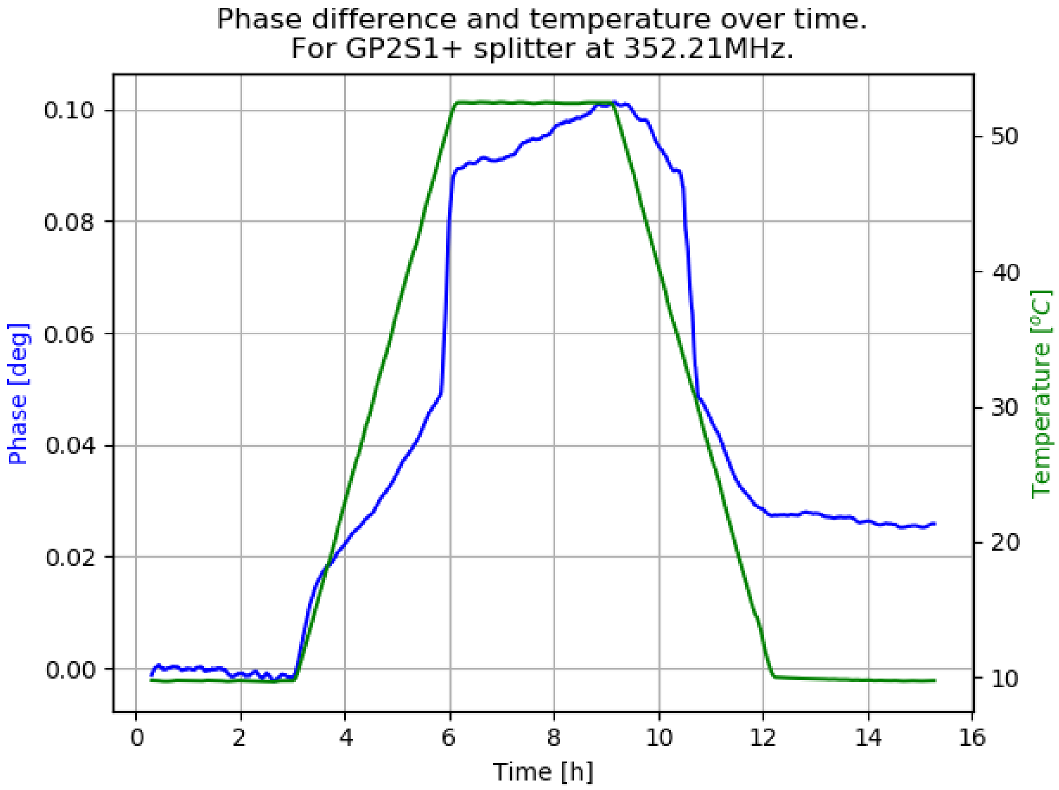

Figure 12. Phase difference between outputs of a single splitter and temperature over time (352.21 MHz).

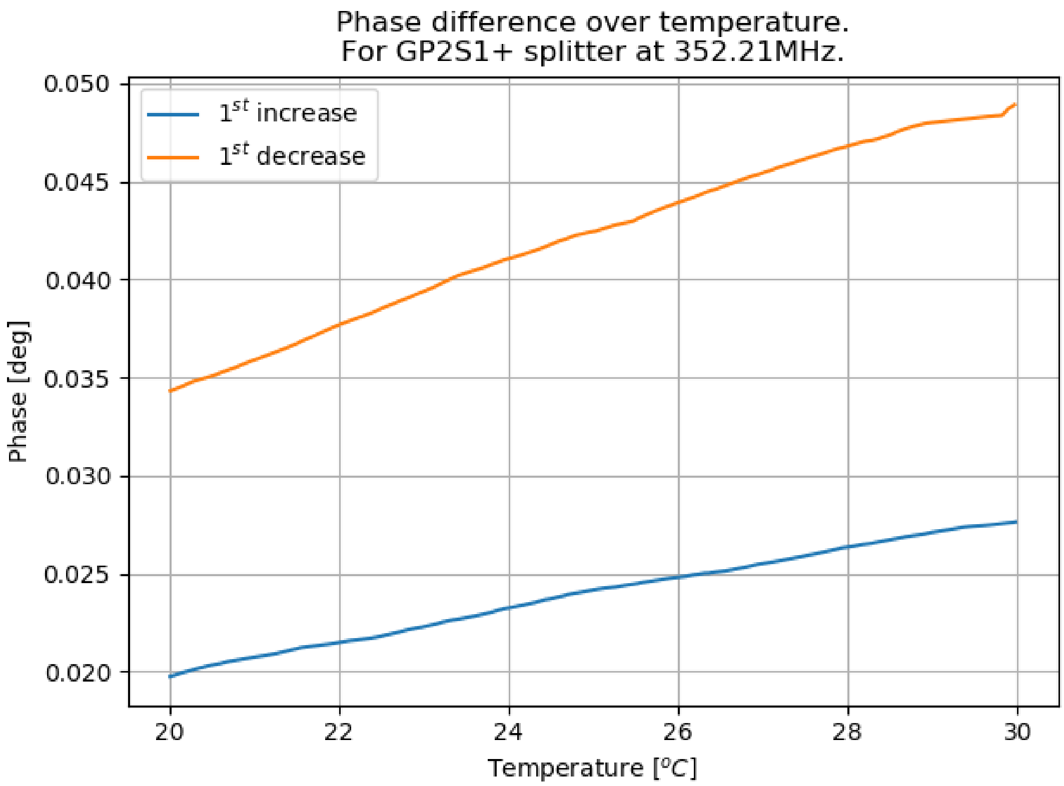

Figure 13. Phase difference between outputs of a single splitter over temperature (352.21 MHz).

Since only the 22°C - 27°C temperature range is significant for the RF SplitBox operation, the data presented in figures 11 and 13 shows only phase difference data acquired for the 20°C - 30°C range.

The phase difference and temperature changes are highly correlated – 0.88 of correlation for the 704.42 MHz and 0.91 for the 352.21 MHz. The linear regression was performed for the data presented on figures 11 and 13. The results along are shown in the table 6.

Table 6. Comparison between first measurement results and requirements.

Frequency [MHz]	Linear regression slope [°/°C]	Allowed maximum phase drift [°/°C]
704.42	0.0014	0.004
352.21	0.0012	

The allowed maximum phase drift was derived from the required 0.02° drift per 5°C temperature change (from 22°C to 27°C).

The results of this measurement confirm that the phase drift between the outputs of a single GP2S1+ splitter are better than the RF SplitBox requirements.

3.2 Phase drift between OUT2 outputs of different splitters.

Second measurement was conducted to determine the phase drift between OUT2 outputs of two different GP2S1+ splitters. The block diagram in Figure 14 shows the measurement setup.

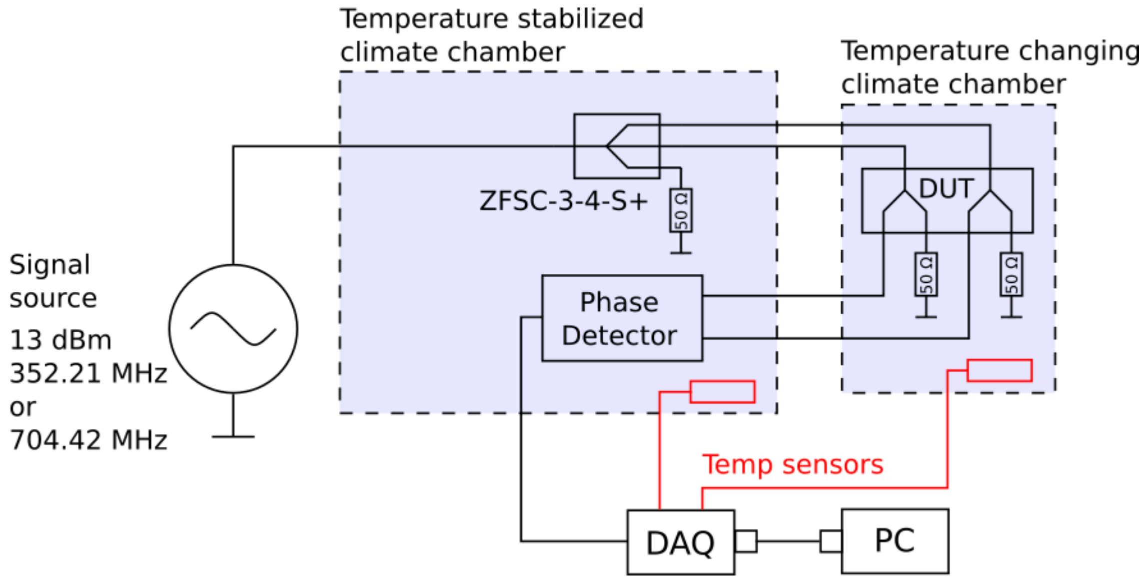

Figure 14. Setup used for a double splitter phase drift measurement.

The conditions were the same as for the measurement of a single splitter. The only difference was that additional power splitter (ZFSC-3-4-S+) was placed in the constant temperature climate chamber – it was needed to feed the signal to both splitters on the test board.

The OUT2 outputs of both splitters were connected to the phase detector inputs with cables of the same type and length, to minimize their contribution to the phase drift measured. All unused ports were terminated with 50 Ω loads. A pair of thermocouples was used to measure temperature changes in both climate chambers.

Because the first measurement done (15 hours cycle) for the described setup gave unexpectedly high phase drift values, it was repeated with 4 temperature cycles to ensure that the results are repeatable. Additional measurement of the setup alone was done, to check if its phase drifts are small enough to be ignored. Block diagram for this additional measurement is presented on figure 15.

Those measurements lasted 51 hours each. Both were done only for the 704.42 MHz signal. The results of those measurements were analyzed together and are presented in Figures 16, 17 and 18.

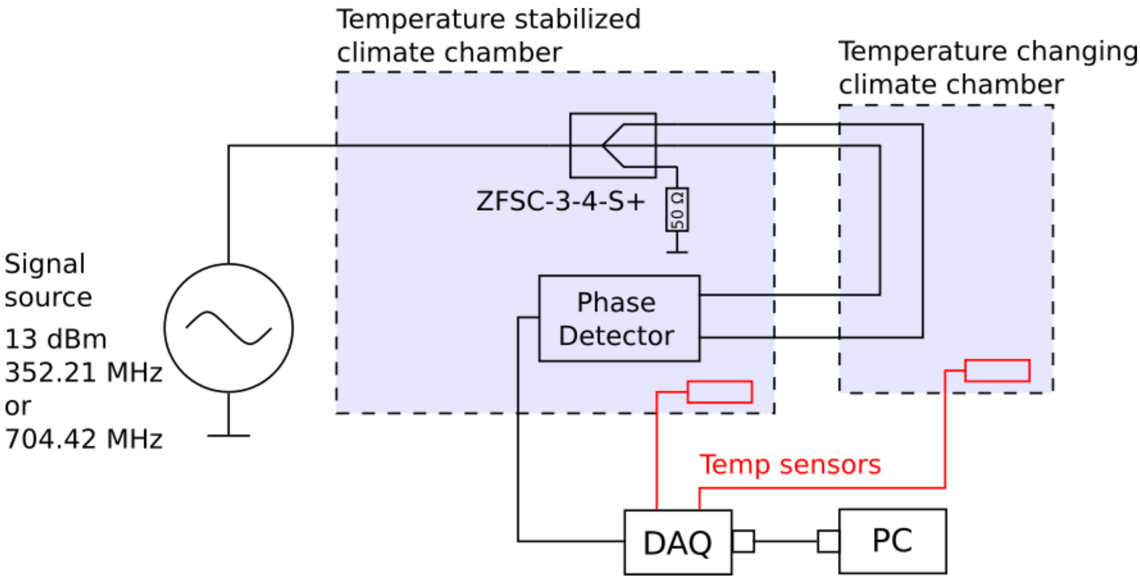

Figure 15. Setup used for additional check measurement.

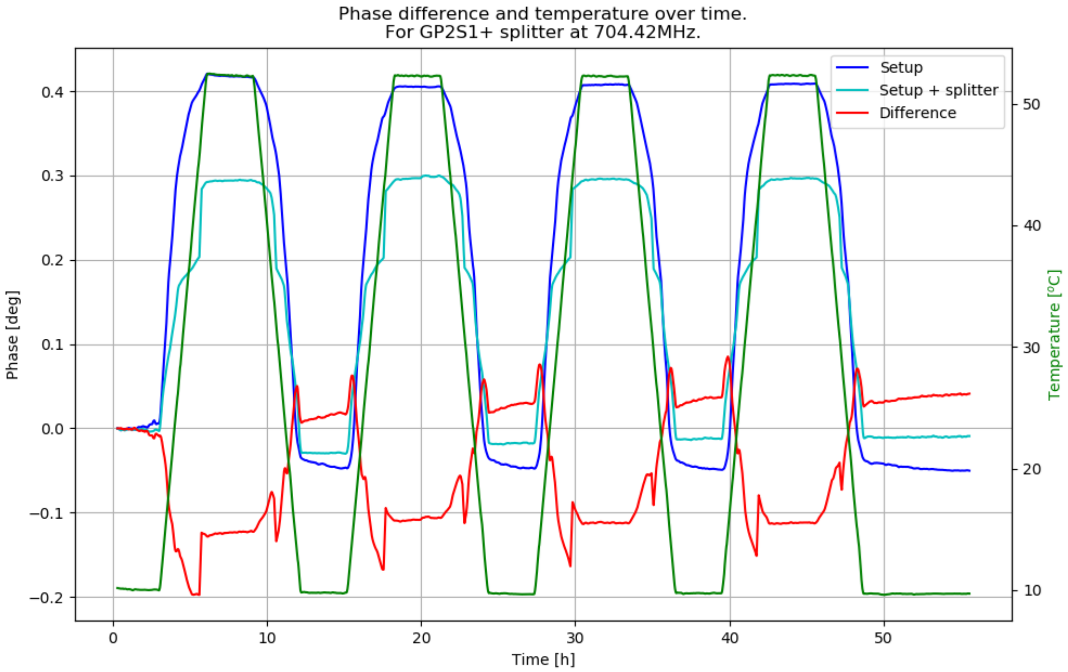

Figure 16. Phase difference measured for the setup alone, setup with splitters and the difference between them.

The additional phase drift measurement done for setup alone(see Figure 15) showed that the setup is contributing significantly to the results. In Figure 16 a difference between the two measurements was plotted to estimate how much is phase drift affected by the splitters presence. This differential phase drift is the shown in Figures 17 and 18.

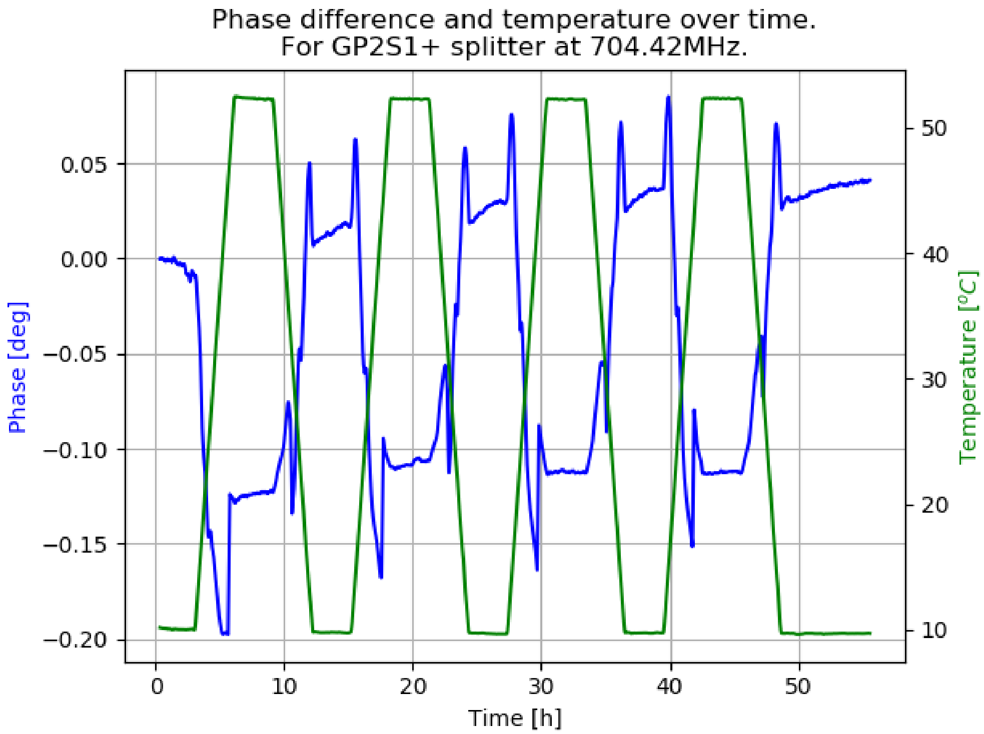

Figure 17. Differential measurement of the phase difference between OUT2 outputs of test splitters.

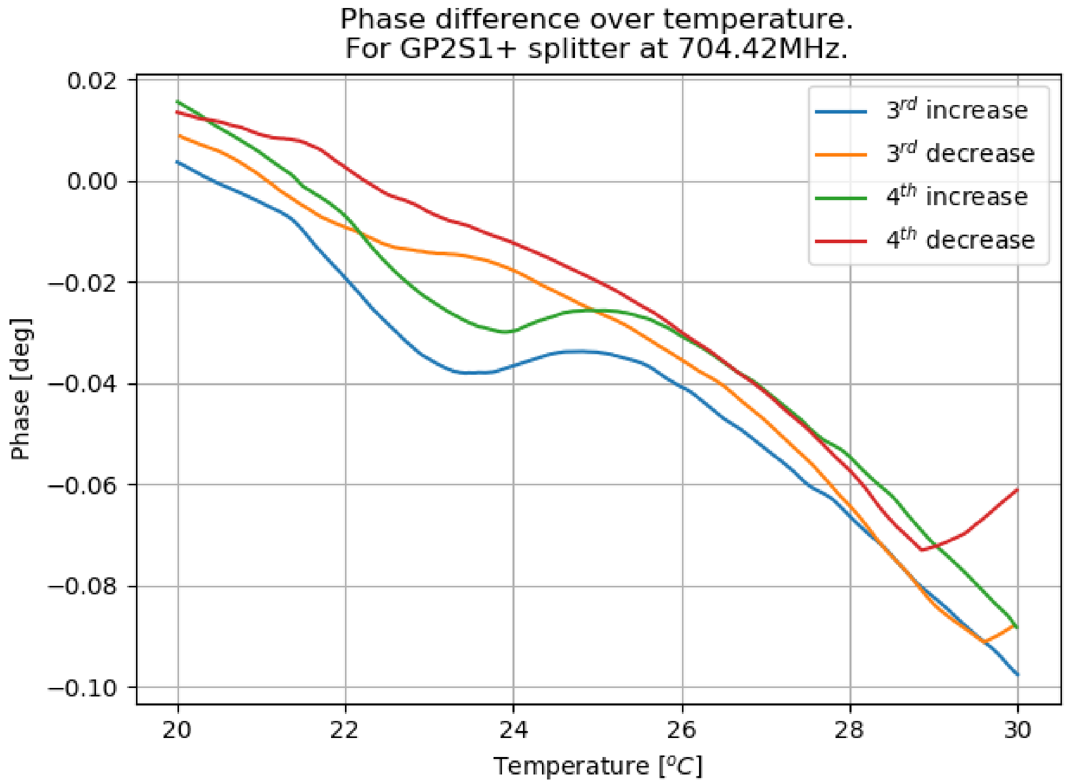

Figure 18. Phase difference between OUT2 outputs of test splitters over temperature.

The data presented in Figure 18 showsphase difference data acquired only for the 20°C - 30°C range. Only the last two temperature cycles were analyzed, because the data presented in Figure 16 shows a difference between the first cycle and the rest – suggesting that the setup may need a warm-up cycle for the results to become repeatable.

The phase difference and temperature changes are highly correlated for all measurements shown on figure 16. Correlation coefficients are as follows: 0.974 for the measurement of setup alone, 0.977 for the measurement of setup with splitters and 0.888 for the differential data.

Linear regression was performed on the data presented in figure 18. The results and the phase drift requirements are shown in the table 7.

Table 7. Comparison of second measurement results and requirements.

Frequency [MHz]	Mean linear regression slope [°/°C]	Allowed maximum phase drift [°/°C]
704.42	-0.0091	0.004

The results of this measurements show that the phase drift between the OUT2 outputs of two GP2S1+ splitters does not meet the RF SplitBox requirements.

However the measurement was affected by large error caused by the test setup. There are several possible source of the error. They will be closly investigated during measurements of the first prototype.

4 Mechanical Design

The device has been designed as a 1U 19” module. All connectors are placed on the rear side of the modules. The 3D visualization of the module is presented in Figure 19. In Figures 20 and 21 the front and rear panel silkscreen are shown.

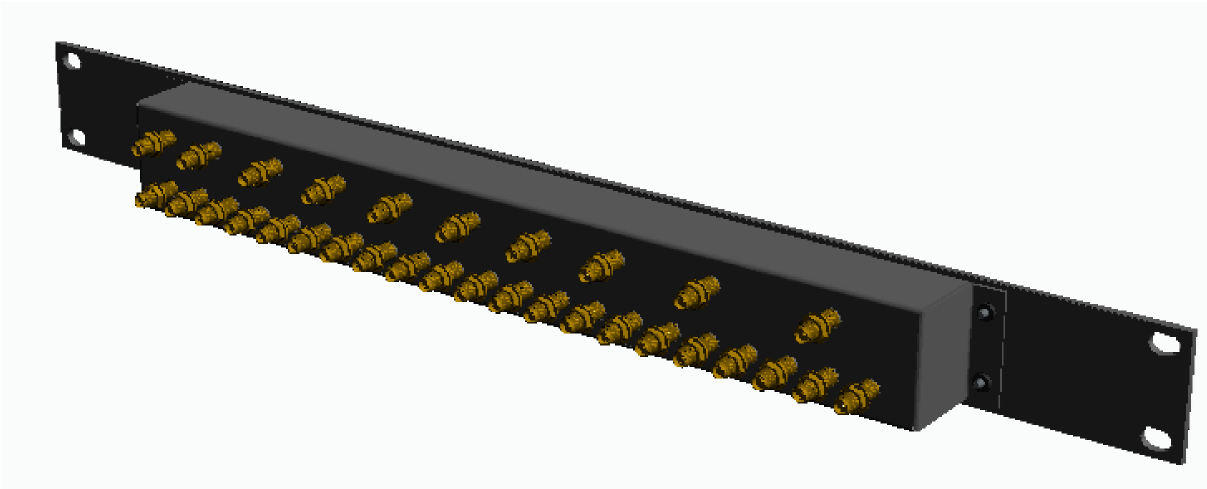

Figure 19. 3D visualization of RF SplitBox

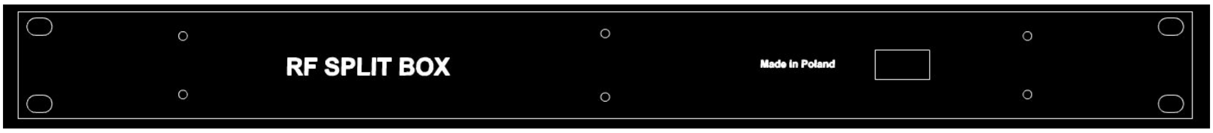

Figure 19. Front panel silkscreen

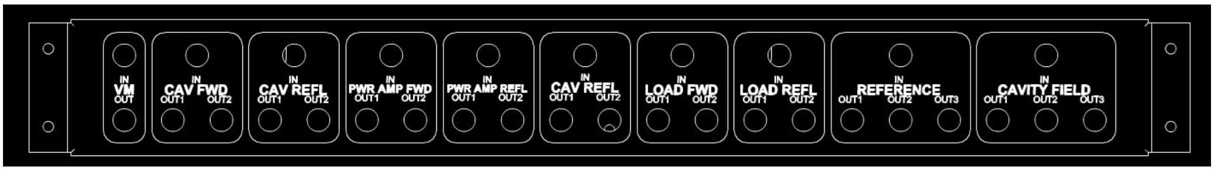

Figure 19. Rear panel silkscreen

5 Summary

RF SplitBox has been designed as a combination of three types of PCB modules. Components were chosen with respect to the technical requirements specified for the device. As of 18^{th} of April the prototypes are being produced for tests.

Two main phase drift measurements were done on the test board with two GP2S1+ power splitters chosen for the project. First measurement, done for outputs of a single splitter, showed that its phase drift is small enough compared to the requirements.

The second phase drift measurement, done for outputs of different splitters, showed a phase drift exceeding the required value. It was shown that the measurement setup is contributing significantly to the measurement results. A modification of the measurement setup will be considered.

6 References

[1] https://ww2.minicircuits.com/pdfs/LFCN-400.pdf
LFCN-400 datasheet, Mini-Circuits (last accessed on 18th April, 2018)

[2] https://ww2.minicircuits.com/pdfs/LFCN-900.pdf
LFCN-900 datasheet, Mini-Circuits (last accessed on 18th April, 2018)

[3] https://ww2.minicircuits.com/pdfs/GP2S1+.pdf
GP2S1+ datasheet, Mini-Circuits (last accessed on 18th April, 2018)

[4] https://www.minicircuits.com/pages/s-params/GP2S1+_S3P.zip
GP2S1+ S parameters, Mini-Circuits (last accessed on 18th April, 2018)