Analysis of an Improved Temperature Management Concept for SAR System Calibration Transponders

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Abstract

For the radiometric calibration of spaceborne synthetic aperture radar systems, active targets with known backscatter, so called transponders, are used. These serve as an external absolute reference, and the quality of the derived calibration parameters depends on the quality of the deployed transponders. Due to the temperature dependent behavior of the implemented active radio frequency components the transponder radar cross section is sensitive to the temperature of the components. This effect requires the implementation of a reliable and precise temperature management system to stabilize the temperature of the radio frequency components to a constant value under all relevant environmental conditions. In order to fulfill the increasing requirements for future transponders towards radiometric accuracy temperature control concepts must be further developed. For this purpose, an existing temperature management systems is analyzed and a control design concept is investigated. Finally the functionality of the implemented temperature management system is verified with measurements of the complete transponder system in a climatic chamber.

1 Introduction

For the radiometric calibration of a spaceborne synthetic aperture radar (SAR) system point targets with well known backscatter properties, e. g. corner reflectors and transponders, are used [1]. Those act as an absolute reference and the quality of the derived calibration parameters inherently depends on the quality of the deployed targets. Any uncertainty in their reflectivity, e. g. caused by thermal variations, influences the calibration of the SAR instrument and consequently the quality of the calibrated SAR images.

A transponder is an active device with a known radar cross section (RCS), determined during an external calibration process [2] [3]. With its implemented RF loop a received signal is amplified, possibly recorded and modified before it is retransmitted to the radar system. The reflectivity is temperature sensitive due to the temperature-dependent behavior of the RF components installed in the transponder. To minimize the corresponding gain drift effects a temperature management system is typically integrated in the transponder which maintains the internal temperature during operation at an almost constant value. This is an important feature in order to ensure the thermal stability of the transponder at different environmental conditions. Together with an accurate knowledge of the backscattering characteristics the stability of the transponder is a prerequisite for an accurate and reliable calibration of a spaceborne SAR system.

2 Thermal Design

The DLR Microwaves and Radar Institute has designed, developed and manufactured new C-band transponders [4] [5], shown in **Figure 1**, which have been successfully operated for ESA's Sentinel-1A mission since April 2014 [6] [7].

Figure 1: DLR Kalibri transponder with cover removed.

These Kalibri transponders are equipped with a well insulated housing and a heat exchanger. For thermal control the heat loss of the active sub-components, e. g. the digital-sub-system (DSS), is used. The thermal transfer is regulated by several fans installed inside the heat exchanger. **Figure 2** shows simulations of the thermal flow inside the transponder. The air-flow follows an S-pattern through the device. By reading out several sensors the temperature within the housing can be monitored and controlled.

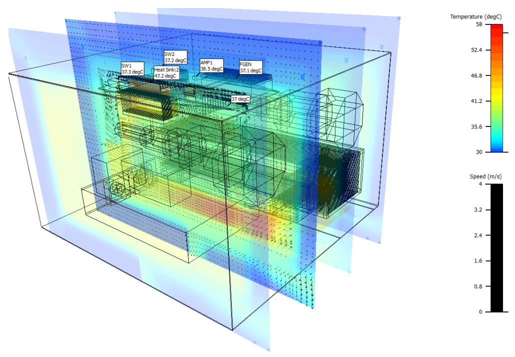

Figure 2: Thermal simulation for the Kalibri transponder thermal design.

3 Gain Drift Compensation and Dependence on Temperature

Serving as reference, the transponder impulse response must be stable after determination of its RCS by an external calibration [2] [3]. For this purpose, a gain drift compensation "facility" is implemented within the Kalibri transponder to minimize gain and phase changes of the radar signal path over time. This compensation is implemented in two steps: monitoring and correction. Therefore a calibration signal is generated by the DSS, fed into the transmitting path, then routed through a gain compensation loop by two radio frequency (RF) switches, and finally recorded again by the analog-to-digital-converter (ADC) of the DSS, shown in **Figure 3**.

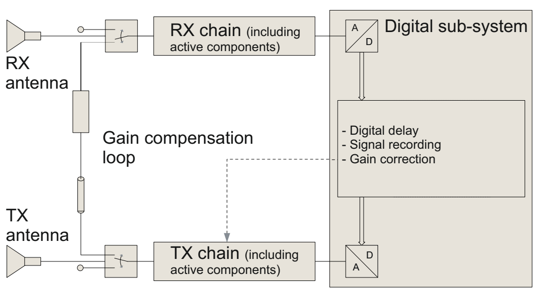

Figure 3: Schematic block diagram of a transponder including a gain compensation loop.

Assuming a constant attenuation in the gain compensation path, variations of the calibration signal must be caused by the receiving or transmitting path. They can be compensated by adjusting the variable attenuator in the transmitting path and by modifying the signal in the DSS. This procedure runs repeatedly and finishes when the gain setting has reached its nominal value, determined during external calibration of the transponder.

4 Temperature Management

Current temperature management systems of SAR calibration transponders are commonly based on a closed-loop control, shown in **Figure 4**. In case of the Kalibri transponders the speed of the fans, integrated in the heat exchanger, is regulated by the controller.

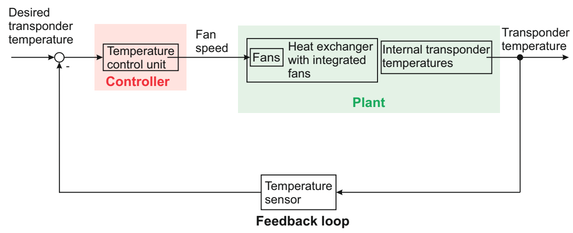

Figure 4: Block diagram of a closed loop temperature controller for a transponder.

In addition to the selection of suitable hardware components for the transponder temperature stabilization (e. g. properties of insulating material , sufficient capacity of the heat exchanger) the design and implementation of a convenient controller algorithm is one of the main challenges. When it comes to erratic environment changes, e. g. caused by extreme weather changes, an unadapted controller can only react inadequately slowly. This can lead to significant RCS changes of the transponder. An example of the gain and temperature drift recorded by a Kalibri transponder is shown in **Figure 5**. Due to unstable temperature conditions (lower diagram) the implemented gain compensation procedure is not able to stabilize the loop gain (upper plot). With a efficient temperature management system the transponder RCS can be stabilized with a precision of 0.01 to 0.02 dB. The shown uncertainty of 0.2 dB at unstable thermal conditions (**Figure 5**, upper diagram) leads to relevant deviation in the transponder RCS. It can be seen that the gain variation correlates with the transponder temperature. This fact underlines the need of an efficient temperature management system because the gain drift compensation is not able to ensure a constant transponder reflectivity under erratic environmental changes.

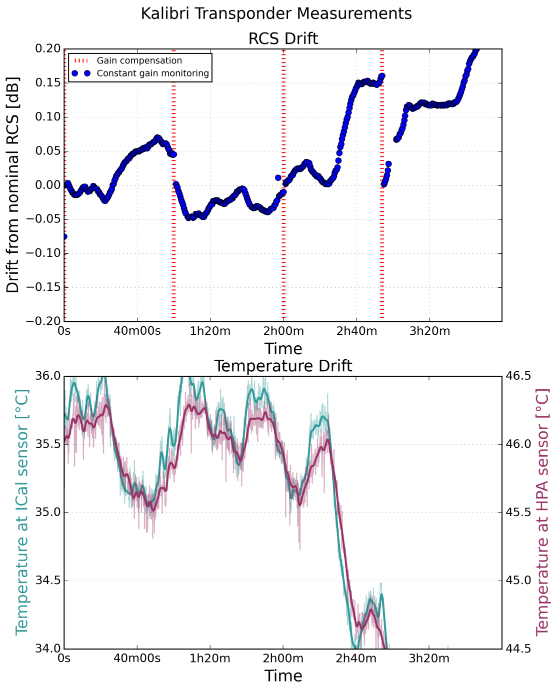

Figure 5: Example for temperature-dependent RCS drift based on data recorded during test measurements.

4.1 Concept for Controller Design

In control engineering the main procedure for analysis and design of a controller are based on an adequate modeling of the controlled section, so called plant. **Figure 6**. shows the fundamental procedure for controller development. From the nominated model equations of the controlled system an adequate control law is derived which in turn is the basis of the realization of the suitable controller [9].

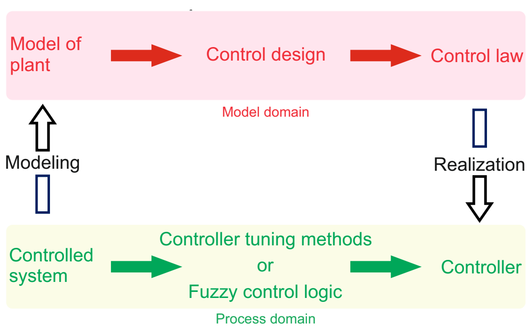

Figure 6: Fundamental procedure for the solution of control tasks according to [9].

In case of the transponder temperature management the realization of the controller design in the model domain can be a difficult matter so that considerable effort has to spent for analysis, simulations, and tests of the transponders thermal behavior. Capturing all influences from all transponder sub-components to a sufficient thermal model can only be reached by operating much effort (i. e. people, facilities for thermal tests, time) to this challenge.

A simpler process to find a suitable controller is a direct design in the process domain. As shown in **Figure 6** the two strategies of controller tuning methods and fuzzy control logicl are available for this purpose. Both methods are promising an adequate control design in order to find a sufficient control algorithm for the transponder temperature management system.

By using a controller tuning method for the design of the transponder temperature controller the properties of the transponders thermal behavior is identified through few experiments with the complete transponder only. No thermal analysis of the transponders sub-components are necessary in order to find the right controller. This is a big advantage with respect to the required effort in comparison to the plant modeling approach described above. The second eligible method is based on the usage of fuzzy logic. Therefore a controller is designed by using the already known knowledge about the thermal behavior of the transponder. All informations are implemented as so called fuzzy rules and processed within a defined logic method to an overall controller [10]. In comparison to the model domain approach this strategy promises lower efforts in order to model the thermal behavior of the transponder. On the other side the efficiency of this method depends on the knowledge about the thermal effects of the transponders sub-components [10]. In comparison to the controller tuning strategy additional effort in characterizations of the overall thermal transponder environment with several sub-component test measurements is expectable because the fuzzy logic needs information of the thermal behavior on sub-components level. At the controller tuning method in contrast few experiments with the complete transponder system are sufficient promising the design of a comparable controller. For this reason the controller tuning strategy is applied for the design of the temperature management concept of the SAR system calibration transponder.

4.2 Identification of Thermal Transponder System

As described in Section 2 the heat loss of the active sub-components combined with a heat exchanger is used for thermal control of the transponder. By regulating the speed of the fans, installed in the heat exchanger, the thermal transfer is regulated. **Figure 7** shows the corresponding hardware setup. According to **Figure 4** the fan speed defines the actuating signal of the control system. This means the control algorithm computes the current speed which is given as a pulswidth modulated (PWM) signal to the fans. Hereby the thermal transfer between the transponder and outdoor environment is regulated through the heat exchanger.

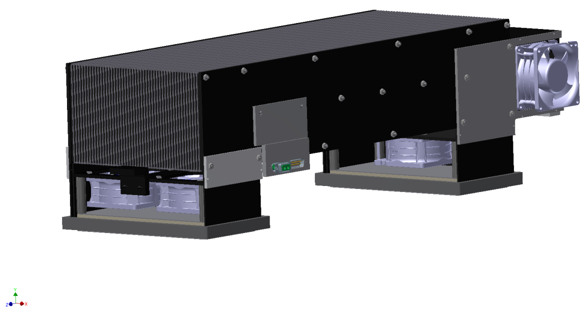

Figure 7: Heat exchanger sub-component with four installed fans.

The performance of a heat exchanger can be approximated as a nonlinear system of first order with time delay [11] [12]. This model can be used for the application of a controller tuning method. The corresponding transfer function is defined as [9]

$$G(s) = \frac{K}{Ts+1} \cdot e^{-s\tau} \tag{1}$$

where K is defined as the gain, T as the time constant, and τ as the time delay. In **Figure 8** the step response is shown.

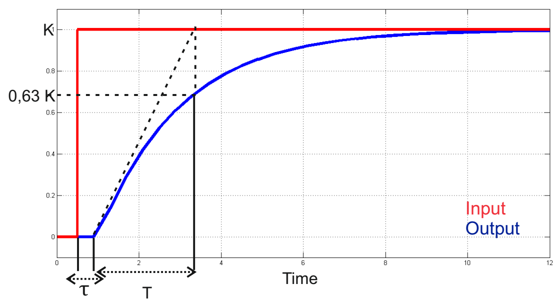

Figure 8: Step response of a nonlinear system of first order with time delay. The system parameters K, T, and τ can be derived from graphical analysis, shown in this Figure.

By measuring the step response the parameters K, T, and τ of such a system can be determined with graphical analysis, shown in **Figure 8**. In case of the transponder the step response can be determined by setting the fan speed on a constant value and measure the temperature to be controlled.

4.3 Controller Design

The proportional plus integral plus derivative (PID) control function is one of the commonest used controller in practical applications. Dependent on the used parameters this algorithm promises a fast regulation of the controlled variable to the desired value without any relevant overshoot [9] [11]. The transfer function of a PID controller ist given by [9]

$$K_{PID}(s) = K_P(1 + \frac{1}{T_I s} + T_D s) \tag{2}$$

where the controller gain K_P, the integral time T_I, and the derivative time T_D are the parameters to be determined during controller design. The performance of the controller depends on the quality of this controller parameters.

With a measured step response of the controlled section and the resulting plant parameters K, T, and τ, the parameters for a adequate PID controller can be derived [9]. Therefore several algorithm are available. A common used strategy is the so called Ziegler-Nichols tuning method [9]. According to this method the parameters for a PID controller can be derived from the following relations

$$K_P = \frac{1,2 \cdot T}{K \cdot \tau}, \quad T_I = 2 \cdot T, \quad T_D = 0,5 \cdot \tau \quad . \tag{3}$$

Together with the controller transfer function, shown in Equation 2, a software PID controller can be realized and implemented to the temperature management system of the transponder. According to **Figure 4** the controller determines the fan speed from the difference between desired and measured temperature. In a closed loop system this process is repeated continuously. When the desired temperature is reached and the system stays in a thermal equilibrium the fan speed is set to a nearly constant value. Without any disturbances (e. g. by sun illumination or rapid changes in the outdoor temperature) no changes are expected.

The step response of the thermal transponder behavior was measured in a climatic chamber at a constant temperature of 17° C. The fan speed was set to a constant value of 40 % of the maximum speed. When the thermal transponder system was in a stable condition (i. e. no longer variation of the controlled temperature) the speed was increased erratically to the maximum value and the temperature was measured. The result is shown in **Figure 9**.

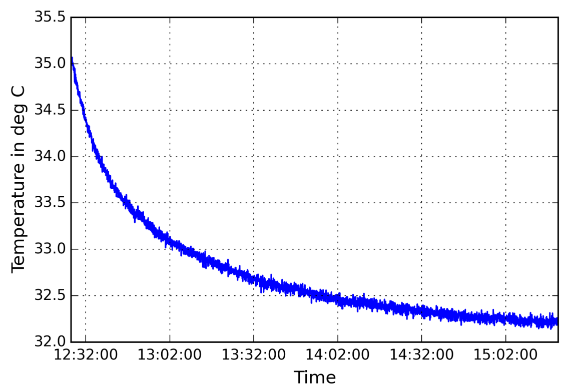

Figure 9: Measured step response of the transponders' thermal system.

It can be seen that the temperature shows a nonlinear behavior. Due to the fact that the transfer of the internal heat loss is increased with a higher fan speed the internal temperature decreases after the erratic speed change. Taking into account this fact the result confirms that the thermal environment can be modeled with a nonlinear system of first order with time delay, like described in Section 4.2. The corresponding system parameters can be derived as shown in **Figure 8**. The results are $K = 0.05°C$ per $\%$ fan speed, $T = 28.5$ minutes, and $\tau = 0.75$ minutes. According to Ziegler-Nichols tuning method, described in Section 4.3, the PID controller parameters were determined with Equation 3, yielding to $K_P = 91\%$ fan speed per $°C$, $T_I = 90$ seconds, and $T_D = 22.5$ seconds.

5 Measurements with PID Controller

The PID controller with the derived parameters from Section 4.3 was realized and implemented into the transponder temperature management system. The controllers functionality and performance was verified with a temperature measurement. For this purpose the transponder was placed inside a climatic chamber with a stable temperature of 17° C. During this measurement all subcomponents were switched on in order to achieve the same internal thermal conditions as in normal operation mode. When the transponder temperature reached a stable value the set-point temperature was reduced by one degree C. Consequently the management system reacts with an increased fan speed and controls the internal temperature to the desired value. **Figure 10** shows the measured temperature behavior of the transponder.

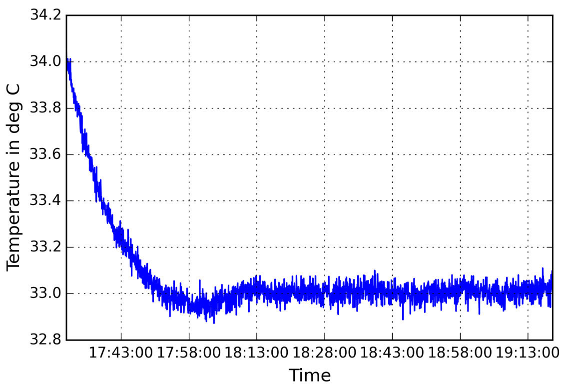

Figure 10: Performance of the transponder temperature management system after changing the goal temperature.

the desired temperature was reached without any significant overshoot. After 30 minutes the transponder has a nearly stable behavior. Consider the fact that during regular transponder operation the goal temperature is set several hours before an upcoming satellite overpass the measured response time of the thermal system can be seen as efficient enough. Furthermore the implemented transponder insulation delays the effect of external thermal disturbances. The designed controller should be able to compensate these changes in a appropriate time so that together with a implemented gain drift compensation the accuracy of the transponders RCS is not be influenced.

6 Conclusion

This paper describes the temperature management system for SAR system calibration transponders. Next to the control design a gain compensation concept is introduced in order to improve the temperature-depenendet accuracy of the transponder RCS. For the design of a PID controller two eligible methods are introduced shortly and their applicability for the transponder temperature management system is compared. Due to effort considerations the controller tuning method is finally recommended as the most suitable strategy. According to this concept the thermal behavior of the transponder system is identified from climatic chamber measurements. The temperature management concept for the transponder is implemented with the derived control parameters. Finally the functionality of the designed management system is verified with thermal measurements. The results show that the chosen tuning method is a proper strategy for the design of a suitable temperature management system for SAR system calibration transponders.

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