Development of a Phase-Sensitive Absolute Radiometer for Space and Ground-Based Use

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ABSTRACT

The Total Solar Irradiance (TSI) varies on all possible timescales. From variations occurring on an hourly basis, like the appearance of sunspots, through the eleven-year solar cycle up to much longer timescales, e.g. several hundred years, like back to the Maunder minimum, or even back to the ice-ages. It is well known that the Maunder minimum is correlated to the little ice age in Northern Europe. However, the physics responsible for these variations is only partially understood. Therefore, it is of great importance to measure the TSI from space.

However, TSI studies do not only give information on the Sun, but are also necessary to understand different contributions to global climate changes, i.e. natural vs. anthropogenic influences. An accurate TSI data set may enable to estimate the possible amplitude variations of the solar irradiance over long time scales and their influence on the Earth's climate.

Additionally, TSI measurements on Earth combined with those in space are of great importance for the understanding of the Earth's energy balance. Therefore, the development of new, more precise instruments is necessary to continue and make more accurate the already 30 year long time series of space measurements and the much longer one on ground.

The aim of our project is to develop a radiometer with a relatively small cavity and thermal capacity, which is based on phase-sensitive signal analysis. With the help of this kind of analysis, many sources of irritation, such as the so-called non-equivalence of the electric and radiative heating, can be eliminated. Radiometers with small shutter periods are suitable for ground-based use as well, as they can handle fast changes in irradiance, i. e. altitude of the sun.

Radiometers with this kind of analysis are already being used in space successfully (Lawrence et al., 2000). Unfortunately, these instruments have a large thermal capacity and are therefore operated with a relatively low shutter frequency of 0.01 Hz, which makes them insensitive to Total Solar Irradiance (TSI) short-term variations, which are encountered during ground-based measurements. However, their relative accuracy is better than 100 ppm. We plan to achieve an identical accuracy for ground-based measurements.

Based on a PMO6 radiometer cavity, a thermal model was developed in order to be able to vary physical properties of the assembly parts such as their materials and thermal conductivity, and thus thermal constants of the instrument's cavity.

We will explain the phase-sensitive signal detection scheme, present the results obtained from the thermal models, and discuss how these two may be connected to minimize the absolute uncertainty.

INTRODUCTION

Measurements of the Total Solar Irradiance (TSI) from space have been carried out since the late seventies, and far longer from ground. It is of great importance to keep these measurements up and make them more accurate.

In this article, we wish to present the status of our project, which is the development and design of a phase-sensitive absolute radiometer. First, the scheme of phase-sensitive signal detection is explained in detail, then we will show the thermal model and the results obtained from connecting these two.

TSI MEASUREMENT

With a PMO6 absolute radiometer as shown in Fig. 1, TSI measurement works as described in the following (Brusa and Fröhlich, 1986):

The back heater, located at the tip of the cone inside the back cavity, is fed with power such that a constant thermal flow is established between the back heater and the heat sink, which is located between the front and compensating cavity. The thermal flux is measured by two resistance thermometers. The heater power is usually around 40 mW, which corresponds to a temperature difference of approximately 0.75 K.

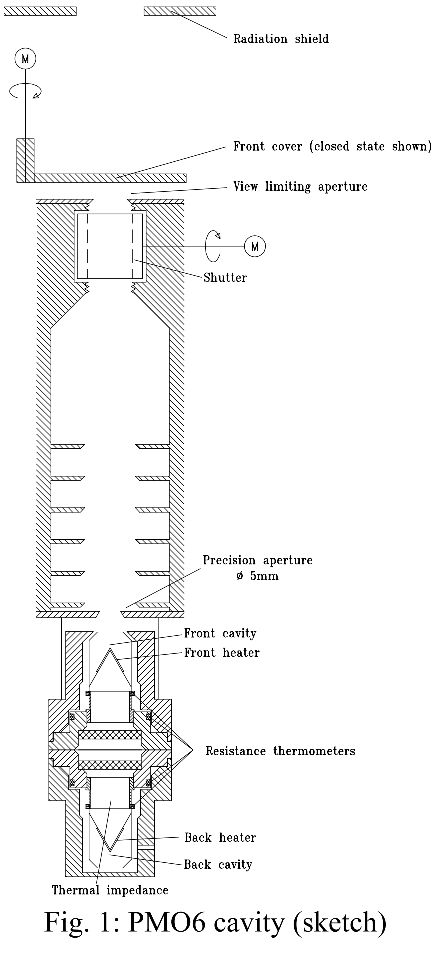

Fig. 1: PMO6 cavity (sketch)

We try to establish the same thermal flux from the tip of the cone inside the front cavity towards the heat sink. When the front cavity is shaded, i.e. the shutter is closed, this is achieved by simply feeding the same amount of power to the front heater as it is done to the back heater. When the front cavity is irradiated, i.e. the shutter is open, the sun's energy is absorbed by the special black paint inside the cavity. The cavity warms up and the heater power has to be reduced by approximately a factor of 2 in order to keep the thermal flow constant. Having a front and compensating cavity allows for absolute measurements, which are generally insensitive to ambient temperature changes.

The heater power of the front cavity is measured. The difference of heater powers while having the shaded and irradiated, respectively, is directly connected to the TSI. Due to the fact that only those measurements can be used when the cavity is in thermal equilibrium, the shutter cycle is relatively long, and only the last few data can be used for evaluation.

A major drawback is the difference in thermal distribution in shaded and irradiated state, respectively. When the shutter is open, a part of the incoming radiation is reflected from the tip of the cone towards the cylindric cavity wall. As a result, the cavity wall warms up, and during ground-based operation, where we have ambient air pressure, a part of the incoming energy is lost through conduction. This is called “Non-Equivalence”, and is the main contribution to the radiometer’s uncertainty.

PHASE-SENSITIVE SIGNAL ANALYSIS

With the help of the phase-sensitive signal analysis, however, we are able to address this uncertainty. Moreover, data from the whole shutter cycle can be used, and long periods of thermal equilibrium are not required for proper detection of the TSI. Therefore significantly shorter shutter cycles and thus a faster measurement cycle are possible.

The TSI coming from the sun, irradiating through the precision aperture A, corresponds to an amount of energy $P_{TSI}(t) = TSI\,A$ arriving inside the cavity. However, due to the principle of absolute measurement, it is chopped by a nearly rectangular shutter function $s(t)$. As the heater control feedback loop aims at keeping the thermal flux at a constant level, we measure a heater power of

$$P(t) = P_0 - P_{TSI}(t) + E(t),$$

where P_0 is the fixed back cavity heater power, and $E(t)$ is an error function mainly caused by non-ideal behaviour of the feedback loop and the non-equivalence.

Multiplication with a sine-wave reference $r(t)$ signal which is in phase with $s(t)$ and integration over one shutter cycle yields

$$\frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} r(t)P(t)dt = \frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} r(t)P_0 dt - \frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} r(t)P_{TSI}(t)dt + \frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} r(t)E(t)dt,$$

where the first summand obviously equals 0. The second summand however is directly connected to the TSI. To take account of the third summand containing the major error functions, the cavity must be redesigned. In general, perturbations on the signal are attenuated perfectly if their phase shift relative to $s(t)$ is close to $\pi/2$, or if their frequency deviates from the reference signal's frequency. This is of great advantage for the accuracy of TSI measurements.

COMPUTER MODEL: CAVITY REDESIGN FOR PHASE-SENSITIVE SIGNAL ANALYSIS

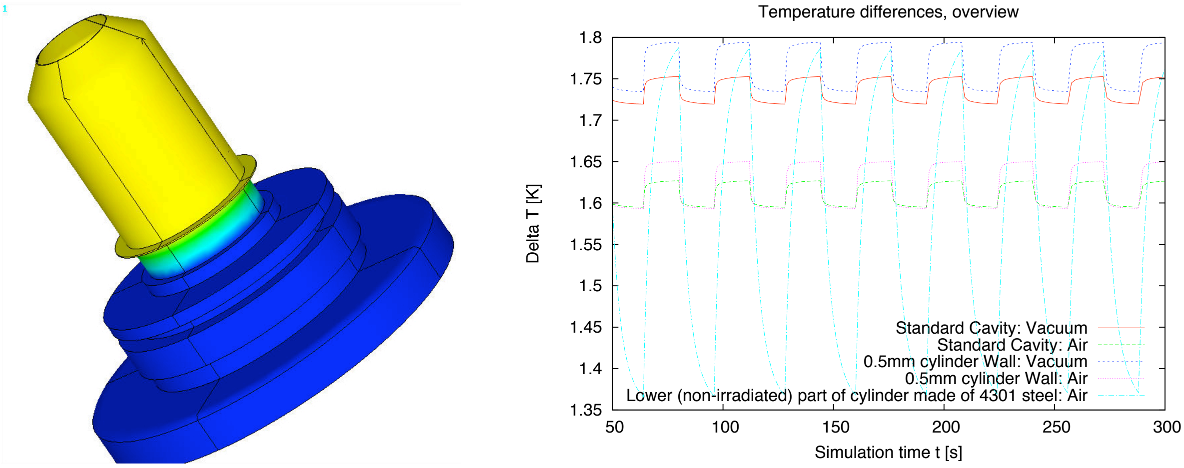

Fig. 2: Left: PMO6 cavity (computer model). Right: Thermal gradient for various configurations

A computer model based on a standard PMO6 cavity was designed in order to investigate its thermal properties and adjust geometry and materials according to the demands of an optimized phase-sensitive signal analysis. So far, we have been able to simulate the thermal behavior of a standard PMO6 cavity with ANSYS® Academic Research FEM software and verify these results by a comparison with data from Brusa and Fröhlich (1986). This serves as a very good starting point for the adjustment of shutter cycle length, cavity geometry and material properties.

CONCLUSIONS & OUTLOOK

We have presented the current status of out project, which is to develop a high precision phase-sensitive absolute radiometer. We have discussed the idea of the phase-sensitive signal detection scheme. Its benefits compared to the classic data evaluation approach lie in the capability of obtaining data with a much higher accuracy during significantly shorter cycles. However, the thermal behavior of the instrument must be known in great detail to take advantage of this new approach.

A computer model has been developed to investigate cavity properties. Although the geometry and material properties can be easily altered, the implementation of a heater feedback loop and the variation of its behavior is a non-trivial task. Nevertheless, this is an important step in reaching the aim of being able to choose an optimized cavity geometry for building a prototype instrument.

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