Teaching thermal wave physics with soils

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In this paper, we discuss the features of a possible student experiment related to the conduction of heat in soils excited by a natural periodically time dependent source, namely the daily periodical oscillations in the earth's temperature, which can be denoted as thermal waves. A measuring device was designed and constructed for automatic measurements of the daily time air temperature variations as well as of the daily time temperature variations, at different depths beneath the soil's surface. Measurements were performed using LM-335 solid state temperature sensors incorporated into a computer-controlled probe. The data acquisition software was developed using a programming environment LabVIEW from National Instruments. In order to obtain characteristic parameters governing the physical phenomena involved, the results of our measurements were fitted to a thermal wave like solution of the heat diffusion equation in the presence of periodical heat sources. The phase shift as well as the attenuation of the temperature waves with depth was demonstrated, as well as their dependence on soil thermal properties, in particular its thermal diffusivity.

Keywords: Thermal waves; soils; thermal properties; thermal diffusivity.

En este trabajo se discuten las peculiaridades de un posible experimento docente relacionado con la conducción del calor en suelos excitados por una fuente térmica variable periódicamente en el tiempo, como son las oscilaciones cíclicas diarias de la temperatura de la corteza terrestre, que pueden considerarse como ondas térmicas. Se diseñó y construyó un dispositivo para la medición automática de las variaciones periódicas en la temperatura del aire así como a diferentes profundidades de la superficie del suelo. Las mediciones fueron realizadas utilizando sensores de estado sólido LM 335 incorporados en una sonda controlada por ordenador. El programa de adquisición de datos fue desarrollado en el ambiente LabVIEW de National Instruments. Para obtener los parámetros característicos que gobiernan los fenómenos físicos involucrados, los resultados de las mediciones fueron ajustados a la solución tipo onda térmica de la ecuación de difusión del calor en presencia de fuentes periódicas. Fueron demostrados el corrimiento de fase y la atenuación de las ondas de temperatura con la profundidad, así como su dependencia de las propiedades térmicas del suelo, en particular su difusividad térmica.

Descriptores: Ondas térmicas; suelos; propiedades térmicas; difusividad térmica.

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1. Introduction

The conduction of heat is a diffusion-like process, where the propagation of thermal energy in a periodically heated solid is well described in terms of thermal waves [1]. These waves have become of great interest for the explanation of the photothermal (PT) phenomena, on which several non-destructive measurement techniques are based [2].

In these methods, thermal waves are generated in a given sample by means of a periodically varying heat source. The changes in the temperature of the sample or in temperature dependent parameters can be monitored. These changes depend, among other things, on the thermal properties of the material of the sample. Therefore, among their several applications, one active area of research nowadays is devoted to their use in the thermal characterisation of materials. Although Ångström in 1861 [3] proposed a temperature-wave method for measuring the thermal diffusivity of a solid in the form of a rod, it was not until the 1970's that practical applications of the photothermal techniques concerning the thermal characterization of solids appeared [4,5].

Consequently, with the development of these techniques, the use of a wave treatment of heat dates from the 1980's [6], although the concept of thermal wave first appeared about hundred years before. Fourier, in his *Analytical Theory of Heat* [7], published in 1822, showed that heat conduction problems could be solved by expanding temperature distributions as series of waves. Fourier, as well as Poisson, have used equations identical to those used today in describing thermal waves in order to estimate the thermal properties at the earth's crust, making use of the daily periodical temperature oscillations [7,8]. In the above-mentioned work [7] Fourier stated that "The problem of temperature at the earth's crust presents one of the most beautiful applications of the theory of heat".

As thermal properties constitute key parameters governing the behavior of many processes in nature, it is of great importance to deal with this theme with students at a college or university level of physics, materials sciences and engineering, as well as the development of student experiments for their measurement. As mentioned in a recent paper [9], the knowledge of thermal properties is of particular importance in the case of soils, because of the role that they play in our food, shelter, and well-being. Seeds, for example, require a certain temperature threshold in order to germinate and develop. Soil scientists are concerned with the effects on the soil properties, including thermal ones, of several natural or artificial processes, such as those of an environmental nature [10]. While in earlier times the effects of pollution were restricted to industrial areas, where increased con-