# Transponders for Altimeter Calibration and Height Transfer

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# Transponders for Altimeter Calibration and Height Transfer

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**Abstract**

Transponders receive altimeter signals and return them, after amplification, to the altimeter satellite. They provide a well-defined reflexion surface of some square-decimeters which replaces the sea surface at virtually any arbitrary point on mainland. As each radar pulse can be detected individually no averaging is required which leads to a significant increase of the precision of the measurements. Applications are manifold leading from altimeter calibration and orbit control to the determination height differences and of very accurate absolute geoid profiles along the ground track of the satellite. The report summarizes the activities of the Graz group and its future plans.

**Zusammenfassung**

Transponder empfangen Altimeter Radarpulse und senden diese verstärkt an das Satellitenaltimeter zurück. Im Gegensatz zu Anwendungen der Altimetrie über Meeresflächen ist die reflektierende Fläche von einigen Quadratdezimetern exakt definiert und der Einsatzbereich für beinahe beliebige Punkte am Festland gegeben. Nachdem jeder Radarpuls eindeutig aufgelöst werden kann, kann auf Mittelungsmethoden verzichtet und die Meßgenauigkeit erheblich gesteigert werden. Die Anwendungsbereiche sind vielfältig, sie erstrecken sich von Altimeter-Kalibrierungen über Beiträge zur Bahnbestimmung von Altimetersatelliten bis zu exakten Höhenübertragungen zwischen der Meeresoberfläche und dem Festland sowie zwischen Punkten am Festland. Aus letzteren können sehr genaue absolute Geoidprofile entlang der Bahnprojektion abgeleitet werden. Der vorliegende Beitrag faßt die bisherigen und geplanten Arbeiten der Grazer Gruppe in diesem Bereich zusammen.

## 1. Introduction

A transponder is a "simple" electronic device which receives satellite altimeter signals and returns them, after amplification, to the signal source.

Unlike the sea surface the reflecting surface is a precisely defined point target which produces, like corner reflectors in satellite laser ranging, unambigous returns. No averaging procedure of different reflection points is required, the returns detected by the altimeter satellite during the transponder's stay in the foot-print show a nice parabolic shape (slant range as a function of time). The value of the slant range at the vertex of the parabola gives the shortest distance between the satellite and the transponder, which is roughly the height of the satellite above the transponder (± 7 mm) if the transponder is located within 100 m of the ground track.

Additional informations can be extracted which are correlated to the along track component of the satellite position. It is a straight-forward matter to measure the time of the received pulses with respect to an external time-reference (e.g. the one per second clock pulse of a GPS-receiver) with an accuracy of ± 5 microseconds. In order to identify the epoch times of the continuous pulse flow hitting the transponder some pulses are suppressed in a systematic way by switching off the transponder for definite periods (like in old optical satellite geodesy) and recording the suppressing times.

The identification of the vertex of the parabola from a large number of measurements (altimeter waveforms) significantly reduces the noise of the altimeter. Variations of the fit procedure show a very stable behaviour of the vertex (some millimetres). It can be emphasized that, currently, transponders introduce errors of below 1 cm in the range and some microseconds in the pulse-timing equivalent to about 10 to 70 cm of the satellite along-track component.

Without going into more details about the reduction of the altimeter data (see e.g. [4]) it is obvious that the determined height is not a true geometrical height but affected by ionosphere and troposphere. To reduce the measured height to a "vacuum" value the total electron content along the signal and the tropospheric zenith delay have to be estimated. As the measurement itself takes only some seconds and is confined to one single frequency, a careful monitoring of the matter between the transponder and the satellite is required in order not to water down the transponder accuracy.

## 2. Ionospheric and Tropospheric Corrections

The height of the altimeter satellite above ground (the transponder reflecting surface) is only biased by signal propagation delays and the altimeter itself.

Informations on the ionosphere are globally available (NNSS, IGS, ionosondes, geostationary satellites, seasonal models) and can be estimated for the particular transponder position by carrying out simultaneous GPS-measurements and mapping the ionospheric component (L4) of each GPS-satellite to the zenith direction. The situation is facilitated by the fact that the influence of the GPS-derived ionospheric parameters on altimeter measurements is reduced by a factor of 50 due to the different wavelengths, but complicated because GPS-derived values determine the total ionospheric delay for a distance of 20.000 km above the earth's surface [1]. The portion of the delay affecting the measurements to e.g. ERS-1/2 at a height of 700 km is difficult to estimate. In summary, we believe that ionospheric delays can be estimated with accuracies of better than ± 10 mm.

On the other hand the means to monitor the tropospheric delay are very cumbersome as in most cases the simple modelling of the troposphere via measured ground-data does not work for the wet part of the partial water vapour pressure. The employment of water vapour radiometers (WVR) combined with informations from weather baloons and distributed ground meteo-data seems to be a prerequisite for keeping the accuracy of transponder derived heights at the level of below ± 20 mm.

## 3. Possible Applications

The employment of transponders for supporting altimetry missions is obvious. The well-defined reflecting surface of the transponder allows for a pulse per pulse analysis of the reflected data as opposed to the averaging procedure applied for "diffuse" surfaces like oceans, ice, or other flat areas. It further enables the use of altimeters in areas of rough topography, virtually in any locality as long as the transponder can be situated along the satellite ground track and no other reflecting surfaces exist in the close vicinity. It operates in a quasi-passive mode, the active components being limited to the signal amplification procedure and the pre-setting of operation-windows to reduce power consumption. In this mode transponders can operate fairly unattended as long as power can be supplied; data accumulation is confined to the source as long as the timing feature is disabled.

The following scenario indicates the possible applications:

Two transponders are situated along the ground track of an altimeter satellite. Their positions are computed by GPS-methods in a global reference frame ITRF (eventually supplemented by SLR). The corrected heights of the satellite above the transponders and eventually above a nearby sea surface are measured by altimetry. The satellite orbit is determined via SLR, PRARE, GPS in the same ITRF. This system defines a closed loop where the misclosures are a measure of the sum of errors introduced by the different procedures (see Fig. 1). If this system covers only a local region some of the quantities are correlated and the errors reduced by forming differences. Dependent on which part of this closed system is examined the following applications can be seen (see also [2]):

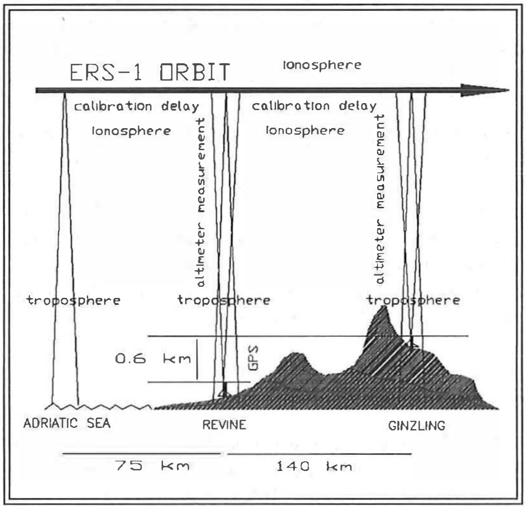

*Fig. 1: Closed self-controlling measurement system realized during the transponder campaign COMPASS II.*

### *3.1 Altimeter Calibration*

If the height of the satellite above the transponder is determined by independent means (SLR, PRARE) transponder measurements can be used for the calibration of the on-board altimeter. A transponder deployment close to a SLR site and tied to this site by GPS removes part of the orbital errors and contributes to the verification and comparison of the altimeter range biases of ERS-1 and ERS-2 simply by comparing laser- and radar-derived distances. Costly arrangements like the "Venice Tower" are superfluous, the transponder behaves like a reference target replacing the sea surface in the gulf of Venice by a considerably more accurate reference surface.

### *3.2 Orbit Determination and Control*

The orbit of ERS-1 is currently determined by combining an accurate model of the gravitational and non-conservative forces acting on the satellite with the somewhat sparse laser ranging data provided by the world-wide network of SLR stations. This situation was improved for ERS-2 by the PRARE tracking system. Transponders tied to ITRF by GPS contribute, point by point, to orbit determination by giving estimates of the radial component (rms about ± 2 cm) and the along-track component (rms about ± 30 cm) independent of weather conditions. Although this method is relatively cost-effective it provides an independent check and assessment of the quality of the global orbital model.

### *3.3 Height Transfer*

Transponders are suitable for providing extremely precise targets for altimeter measurements in a rough topography. If the satellite orbit is precisely known, with exception of a translation, this orbit can be used to "transfer" the height of a terrestrial transponder site to another transponder site. In addition, transponders provide a link between the coastland and the mean (averaged) sea surface (playing the role of a tide-gauge for the time of the overpass). It is evident that uncertainties in the orbit play a secondary role the shorter the "transfer distance" is. Likewise, a considerable part of the atmospheric delays is cancelled, leaving the problem to model local effects. Altimeter measurements are only subject to zenith delays, the high frequency band damps ionospheric delays, they provide an independent, nearly model-free method to complement and verify GPS height determination on mainland.

### *3.4 Monitoring of Uplifts and Subsidences*

Transponders allow the automatic collection of data in unattended mode for long time periods. Although the data-rate is pretty low (10 datasets per year for a 35-days repeat orbit) it is sufficient to monitor vertical displacements, especially in perilous environment like near volcaneous or on ice caps.

### *3.5 Absolute Geoid Profiles*

All applications discussed so far are based on purely geometrical considerations (apart from orbit modelling and the definition of the sea surface). Earth physics comes into play when deploying several transponders along a ground track, combining SLR orbit determination, altimetry and orthometric height control, and comparing it with GPS + orthometric height derived geoid heights.

## 4. Experiences in Height Transfer

Based on an idea of R.J. Powell [3] two transponders (NORDA, ESTEC) were deployed along the Venice arc during the calibration phase of ERS-1 and the following month (COMPASS II) in order to demonstrate the efficiency of transponders as altimeter targets on mainland using the concept of height transfer. Utmost care was taken to monitor atmospheric conditions during the overpasses and to tie the transponder locations at Revine (Italy) and Oberböden (Austria) by GPS. Relevant details are reported in [4], a further joint report will be published this year by P. Cross, University of Newcastle upon Tyne.

Altogether five common ERS-1 overpasses could be detected, the final result for the "height-misclosures" was shown to be

$$2.8 \text{ cm} \pm 2.6 \text{ cm}$$

indicating that in spite of the various error sources the applied method leads to very satisfactory results.

In view of this promising result ISRSG Graz purchased a newly designed transponder version including the timing option for monitoring the along-track component of the satellite orbit (see Fig. 2). As a pilot project, the demonstration of the transponder technique for monitoring the height of the SHELL oil platform Brent (160 km north-east of Shetland Islands) by height transfer to Schindlet (near Zurich) was conducted using the ERS-1 overpass on Sunday, July 10, 1994 at 21.20 UT. The new Graz transponder was deployed at Schindlet. After a quick-look analysis of the altimeter data carried out by Rutherford Appleton Lab. the results for the Graz transponder suggest an uncertainty of ± 1 mm in the vertical and ± 40 cm for the along-track which confirms the expected specifications. The final results [5] show that the precision of altimeter de-

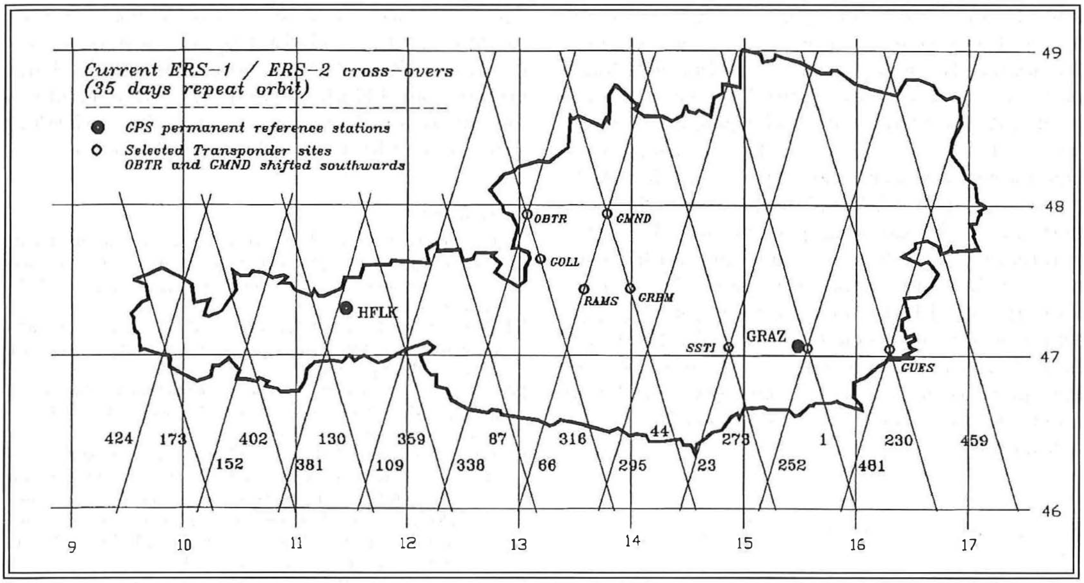

*Fig. 2: ERS-1/2 Subtracks in Austria (35 days repeat orbit)*

rived height differences is in the order of ± 3 cm, consistent with COMPASS II.

## 5. ERS-2 Altimeter Calibration and Orbit Determination

In response to the ESA Announcement of Opportunity for ERS-1/ERS-2 a common project "The Use of Transponders with ERS-1 and ERS-2 Altimeters" was worked out by Rutherford Appleton Laboratory (Didcot, UK), Geodetic Institute of the University of Newcastle upon Tyne (UK), Royal Greenwich Observatory (Cambridge, UK), Geophysical Department of the University of Copenhagen (Denmark), and Institute for Space Research (Graz, Austria). Special emphasis was laid on the role of transponders (4 of them are presently available in Europe) for the calibration of the ERS-2 altimeter and a direct comparison with ERS-1, which are presently operating in a tandem-mode (identical 35-days repeat orbits with 1 day separation).

The transponder measurements were originally planned to be carried out at five cross-over points (intersec-

*Fig. 3: Graz Transponder deployed at LASS (near Lustbühel)*

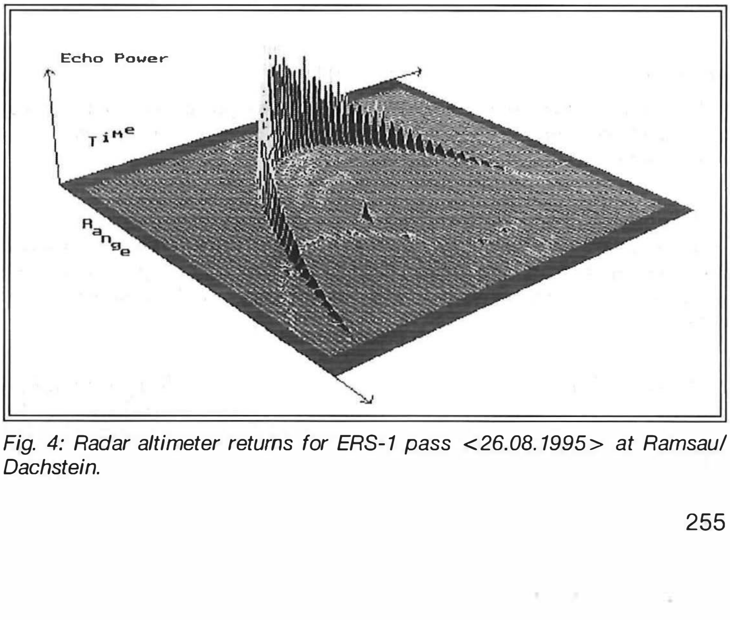

*Fig. 4: Radar altimeter returns for ERS-1 pass <26.08.1995> at Ramsau/ Dachstein.*

tion of north- and south-going passes) displayed in Fig. 3. Two of them showed too many local reflections to be of any further use, therefore three new sites were defined along the particular subtracks. As an example the radar altimeter returns for an ERS-1 overpass at RAMS (Ramsau / Dachstein) are shown in Fig. 4. All sites were connected to the International Terrestrial Reference Frame by preceding or on-site GPS-measurements, the latter also being used for the estimate of the ionospheric corrections. Special attention is paid to the cross-over point LASS, situated in the near vicinity of the Graz laser station (7 km) for which altimeter derived heights and laser distances are highly correlated and can be used for a direct calibration of the ERS-2 altimeter.

## 6. Current Status and Future Plans

The recent measurements have shown a substantial decrease of the power of the emitted return pulses by a factor of 8 compared to the first measurements in Schindlet, which complicates the data reduction for noisy sites. The reason may be the failure of one amplifier inside the transponder which is presently investigated. After some test-measurements near the observatory Lustbühel it is planned to repeat the measurements in Austria for a further 70 days period. After that the Graz transponder will be employed, together with the Copenhagen transponder, for a dedicated mission which aims at the connection of North Sea and the Adriatic on the one hand and the connection of the individual sea surfaces to the coastland on the other.

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# On the Separation of Gravitation and Inertia in the Case of Free Motion

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### Abstract

The authors explored the possibility of separating gravitation from inertia in the case of free motion according to general relativity, proposed a general method of determining the relativistic gravity field of the earth, and put forward and proved two important statements.

### Zusammenfassung

Die Verfasser untersuchten die Möglichkeit der Trennung von Gravitation und Trägheit in dem Fall der freien Bewegung gemäß der allgemeinen Relativitätstheorie. Es wurde eine allgemeine Methode zur Berechnung des relativistischen Gravitätsfeldes der Erde vorgeschlagen. Weiters wurden zwei wichtige Theoreme aufgestellt und bewiesen.

## 1. Introduction

Quite a few geodesists paid attention to relativistic effects in geodesy [2, 5, 7, 8, 12]. It is generally agreed that, if an order $10^{-8}$ – $10^{-9}$ or a higher accuracy requirement is needed, the relativistic effects should be considered.