RECONSTRUCTION OF GRAIN SIZE DISTRIBUTIONS FROM QUASI-STATIC SOIL PENETROMETRY EXPERIMENTS

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Abstract

Mechanically ground–penetrating instruments, widely used in geotechnical practice, can also yield valuable information about texture and mechanical properties of solid surfaces of planets and moons in our solar system (Kargl et al., 2001; Kömle et al., 2001; Kolb et al., 2005a). The most recent example is the Huygens probe landing on the surface of Titan (Zarnecki et al., 2002, 2005). In this paper we will demonstrate the kind of information that can be derived from quasi–static and dynamic penetrometry measurements. We will show examples of penetration experiments performed in preparation for future Lander instruments. The main work in this paper will focus on the detection of small–scale structures and their signatures in a penetrometer signal, namely resonances forced by semi–regular scales (granularity) and boundary crossings (layers). The study of resonant oscillations in the signal allows an approximation of the average grain size distribution within the penetrated distance. Despite the fact that the main direction of our research was focused on extraterrestrial solid surfaces, our results may likewise be useful for geotechnical engineering applications.

1 Introduction

Penetrometry is the probing of a surface material via the insertion of an instrumented test projectile. This method originates from terrestrial applications, which are quite common and standardized for engineering and geotechnical purposes (Lunne et al., 1997). For space applications we can generally discern between two major methods, which basically differ in the speed of insertion and the type of the returned data. Such measurements have been partially employed at the Russian lunar rovers and the Venera landers (Lorenz and Ball, 2001), and were proposed for various missions to the planet Mars. They are

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also implemented on the *Philae* Lander of the Rosetta mission to comet 67P/Churyumov–Gerasimenko (Spohn et al., 2007). Until now, the most successful application of such a method was the Huygens probe landing on Saturn's moon Titan on 14 January 2005, where the ACC–E sensor of the *Surface Science Package* (Zarnecki et al., 2005) delivered penetration data from the first 5 cm of Titan's soil. Usually penetrometry data are used to gain information on the hardness of the investigated soil. In this paper, however, we will demonstrate that by analyzing the noise structure of a penetrometry signal one can extract information on the structural elements of the soil. By applying a Fourier transformation on the signal we investigate that part of the signal which is usually removed as noise and deduce the grain size distribution of the penetrated soil.

2 Cone pentration test

2.1 The penetrometry facility

For laboratory penetrometry experiments a test facility for quasi–static experiments was set up at the *Space Research Institute* in Graz. It is shown in Figure 1. The initial purpose of this facility was the development and test of a small penetrometer sensor for the planned *Mars NetLander* mission, but the measurements were continued throughout the years 2004 and 2005 after the cancellation of the *NetLander* project. Major differences to standard terrestrial cone penetration tests are that the whole device is much smaller in scale and restricted to lower force levels. Moreover, the maximal penetration depth is usually less than one metre. The advantage of this smaller scale is that the used sensors are much more sensitive to tiny structural variations of the soil along the penetration path than their larger terrestrial counterparts.

With this facility we can perform experiments in Martian soil mechanical analogue materials, i.e. dry granular materials. The penetrometer is driven by an industrial linear actuator with insertion speeds of ≤ 14 mm/s. A maximum penetration depth of approximately 25 – 30 cm can be reached. At the lower end it consists of an 18 mm diameter steel rod with 200 mm length and exchangeable load cells on both sides of the rod, where the lower sensor is called "Test Sensor" and the upper one is referred to as "“Monitor Sensor". The force ranges available for these sensors are 25, 100, 500, and 1250 N. An exchangeable tip is mounted on the penetrometer rod just beneath the lower sensor. For our experiments we could choose between five different tip geometries, namely 30°, 45° and 60° opening angle cones, a half sphere and a flat cylindrical tip, as shown in Figure 2.

The whole probing and data acquisition process can be controlled by software, where both the sensor signals and the rig status are monitored with a typical sampling frequency of 1500 Hz. From the sampled data the speed and depth of the penetration can be reconstructed. These data were then used for the calibration of a cone penetration model programmed in the finite element software ABAQUS (Zöhrer, 2006; Zöhrer et al., 2006). An example of a model calculation result in comparison with a measured penetration depth versus force curve is shown in Figure 3.

Figure 1: The penetrometry test facility used for quasi–static experiments in Martian soil analogues.

Figure 2: The standard tips used for the cone penetration test. The leftmost have a conical shape with 30°, 45° and 60° opening angle respectively, followed by a half spherical and cylindrical shape.

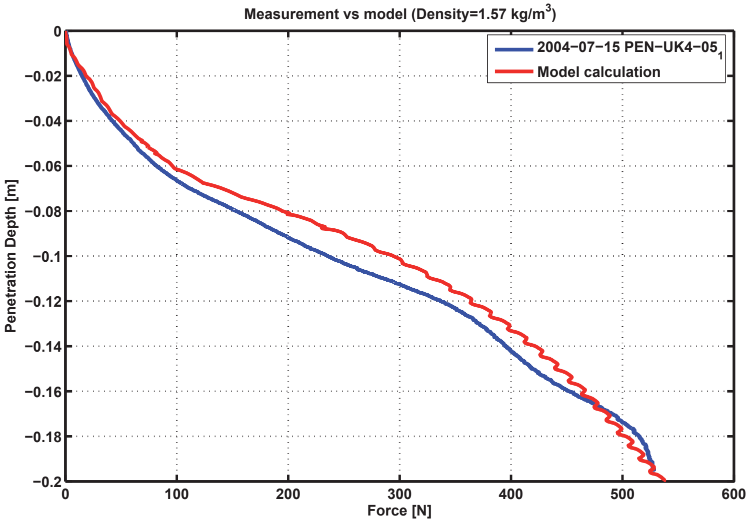

Figure 3: The penetration force measured and computed with a finite element software.

3 Used materials

As sample material for our cone penetration tests we used materials suitable as mechanical Mars surface analogues. Most of the tests were done to support the calibration of a cone penetration model. Therefore the bulk of the tests were made with a local sand (UK4) which has more or less the same grain size distribution as the Martian soil standard JSC–Mars–1 (Christensen et al., 1992). UK4 is a natural sediment available locally from a region south of Graz/Austria. It is mostly comprised of quartz and some minor amount of feldspar. The material was pre–treated by sieving to obtain a maximum grain size $<$ 1 mm. Since the geomechanical parameters of this material are similar to those of the NASA material JSC–Mars–1, we consider it for mechanical penetration tests as equivalent to the standard material.[1]

The second material we were using was the *Salten Skov* iron precipitate from Denmark which was obtained from the Aarhus University in Denmark (Merrison et al., 2001). The precipitate was formed by oxidation of Fe^{2+} dissolved in ground water which was transported to the surface by a spring. The iron is supposed to originate from pyrite bearing layers (Kolb et al., 2005a,b). At the site, it can be easily excavated from the ground and is still available in large quantities. The material was pre–treated by removing larger organic contaminations as roots and leaves and then sieved to remove grains larger

[1] The reason why JSC–Mars–1 was chosen as a Mars analogue material was mainly due to its matching IR spectral properties. However, since then it was widely used as a standard Martian soil simulant because of its availability to the scientific community.

than 1 mm. When becoming moist this material tends to form clusters which easily break again under mechanical stress. Its major use up to now was the investigation of dust uplift mechanisms in a Martian environment, but beyond this it is now becoming some kind of “European standard” as Mars analogue material since more and more laboratories are using it for various purposes. Its general mineral composition and grain distribution is thought to be more close to some regions of Mars than the JSC–Mars–1 material. A more detailed description of all the sample materials used can be found in Zöhrer and Kargl, 2006.

4 Small scale structure detection

The usage of cone penetration tests as a means to obtain soil profiles for e.g. foundation engineering has become more or less a standard procedure over the last decades for terrestrial applications. Test results are usually used to estimate soil strength and stress–strain properties of the probed areas (Lunne et al., 1997; Zöhrer et al., 2004; Zöhrer, 2006).

4.1 Signal fine structure

If we want to obtain more information on a soil than the above mentioned soil mechanical properties we need to analyse the signal in more detail. Usually, when interpreting a penetrometry signal we are only interested in the general trend. This is obtained after applying various calibration and filtering processes. However, if a highly sensitive system is used, we can notice that there is a certain level of noise in the signal. Some of this noise is systematic, e.g. a mains hum, mechanical noise from gears or the drive motor. If we are able to eliminate these sources of disturbances we find that there is still some information left in the signal, which is related to the structure of the sample material. To obtain a more quantitative measure for the remaining information content, we postulate a very simple relationship between a regularly spaced structure and the speed a penetrometer is moving through this structure. This allows us to define a mechanical excitation with the frequency f as:

$$f = \frac{v}{l} \tag{1}$$

where f is the frequency exited by interaction with equally spaced structures with a scale length l, moving along with speed v. A natural granular soil is of course not exactly equally spaced. However, given the fact that penetrometry tests comprise usually huge data sets we can expect to encounter many similar structural elements within one penetration test. Therefore, when the signal is recorded with a suitable high sampling frequency, a whole spectrum of excited frequencies is obtained. Each grain interacting with the corpus of the penetrometer leaves a small impact signature. Summing up all these small contributions during the penetration we obtain the total penetration resistance. Asserting a naturally sorted soil (i.e. all grains having a probability of interaction directly proportional to their occurrence in the material) we can expect to find their trace in the noise spectrum of the

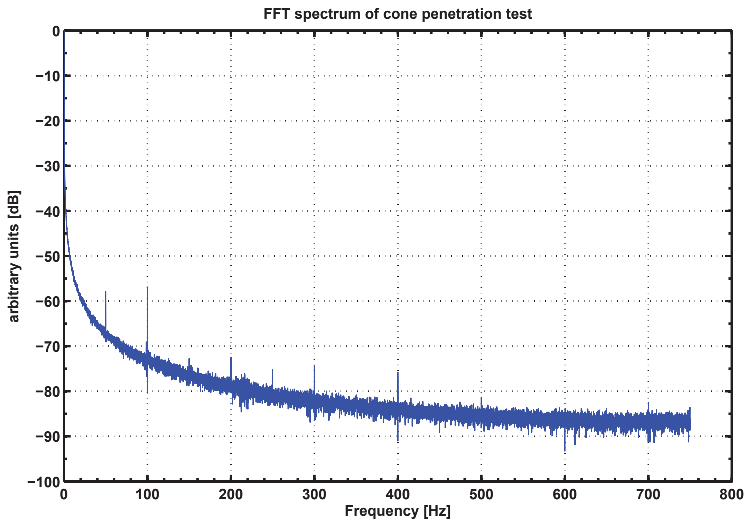

Figure 4: FFT power spectrum of a penetration test into an UK4 sample.

signal according to Eq. (1). Naturally, more common particle or structural sizes should give rise to a higher and more pronounced spectral signature.

4.2 Noise spectrum

To derive a noise spectrum we have to start with the FFT spectrum of the raw penetrometry data (Figure 4). The only processing of this data was a 3–point median filtering to reduce the digitization noise.

For the derivation of the noise spectrum the bare–bone background of the signal has to be removed. For this purpose the raw data were filtered with the consecutive application of median– and Hanning–windowed sliding average filters. The resulting signal is sufficiently noise free and can also be used as a reference for cone penetrometer modeling. From this cleaned signal an FFT spectrum is computed as well and then subtracted from the spectrum of the original signal. The residual spectrum can then be used for the derivation of the noise spectrum. The usable frequency range is restricted to a frequency band defined by signal theory. From the *Nyquist* theorem it follows that only frequencies below half of the sampling frequency can be resolved and used as upper boundary. From the total amount of sampled data points we can compute a lower minimum frequency, but for the sake of simplicity and comparison purposes 1 Hz was used as lower frequency limit. After that the standard deviation s is computed for the residual spectrum F_R and the spectrum is then normalized (F_n) to a multiple γ of the standard deviation expressed in dB units. Figure 5 shows a normalized noise spectrum obtained by the procedure described above.

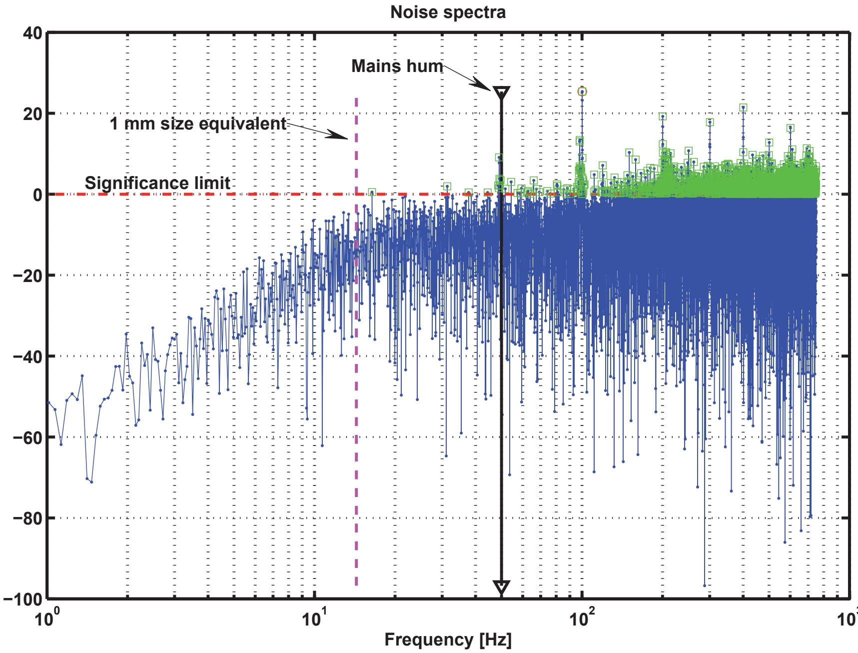

Figure 5: Normalized noise spectrum of a penetration test into an UK4 sample. Only parts of the spectrum which are above the threshold have been considered for the size distribution count.

$$F_n = 20\ log_{10}\left(\frac{F_R}{\gamma s}\right) \tag{2}$$

The reason for the normalization is the suppression of statistically insignificant components i.e. only structures which have a high impact on the signal are accepted for further analyzation. As an additional precaution all peaks around the mains hum (50 Hz) are removed from the spectrum. All remaining peaks in the resulting noise spectrum are then identified by their centre frequency and counted by a software routine. With the known penetration speed the frequency can be converted into a structural size (Eq. (1)). For a better handling the size count is binned into boxes spaced after the *ISO* standard mesh sizes (*ISO 3310–1*). Since for a natural material the smaller structures give a much larger count rate than the large structures the resulting histogram is imbalanced by the difference in total count numbers which easily can be three to four orders of magnitude larger for small sizes and therefore difficult to interpret. Thus, to extract a meaningful information out of the data we have to display them in a way which is used as an engineering plot standard for grain size distributions of soils.

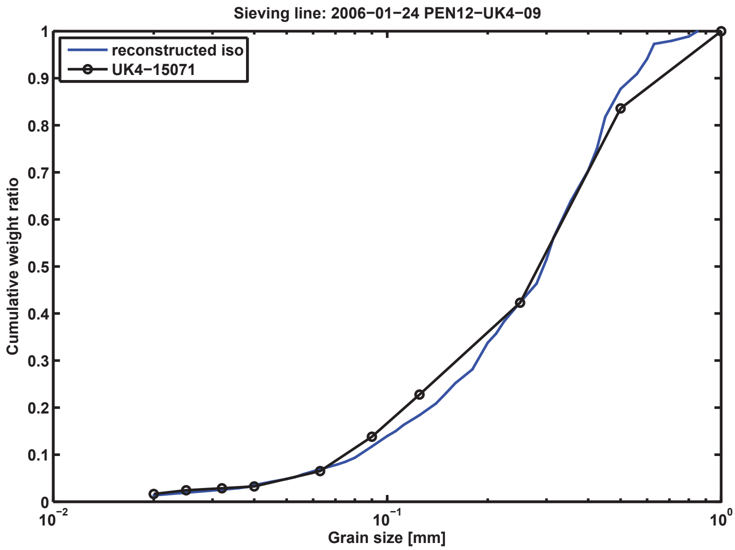

Figure 6: Cumulative grain size distribution for UK4 sand.

4.3 Sieve line plot

Natural soils are characterized by the distribution of grain sizes within a unit volume of soil. For this the soil is processed by a standardized stack of subsequently finer and finer meshed sieves. After that the fraction of material remaining in a specific sieve is weighted and can be plotted in a size–weight diagram. As an engineering standardization the size distribution is displayed in a cumulative weight plot normalized to the total amount of soil used for the measurement. Thus a graph is created which can easily be compared with measurements for other soils or from other laboratories. Moreover, cumulative plots are less sensitive to measurement inaccuracies affecting single size fractions, since the total amount of material is preserved even if e.g. a differently meshed sieve line is used by some laboratories. For really small fractions in the soil (particles < 0.063 mm) the method of sedimentation can also be used (*CEN ISO/TS 17892–4 2005*).

If we now want to compare the grain size distribution derived from the noise spectrum of a cone penetrometer test it seems to be a natural way to display it in the same form as the engineering standard plot. For this, the size counts are converted into mass fractions assuming spherical grains and plotted in a cumulative weight–size diagram (Figure 6). Since the plot is normalized to the total mass of the grains it does not matter whether the soil density is known or not.

4.4 Limits of the method

At this point the limits of the above described method need to be investigated, in order to undrstand the quality of the results. First of all this is a statistical method and the probability of encountering a significant amount of each size population has to be kept in mind. For the larger diameter grain fractions in a soil the probability of being hit by the cone penetrometer is lower, since usually the bulk volume is dominated by the smaller diameter grain fractions. Thus it can not be guaranteed that for large grains a sufficient count rate is obtained with one measurement. Some large grains might not at all be along the trajectory of the cone penetrometer. On the other hand large grains tend to dominate the mass fractions of a soil volume since the mass or volume is proportional to the third power of the grain radius r. The solution is to increase the total available number of data points by a deeper penetration or the usage of more than one measurement to increase the statistical significance of the larger grain count rates.

For the grains on the small scale side of the grain size distribution, we have to deal with the sensitivity of the measurements. The single grains, at some point, are becoming too small to have a noticeable impact on the cone penetrometer and might not be seen anymore in the data. Another limiting factor is the sampling frequency of the instrument, which is essentially determining the size of the smallest fraction we are able to see in the spectrogram. Thus, for very fine grained silty materials the contribution might be too faint or simply beyond the detection limit of the measurement. In the extreme, if we encounter a very silty material, we might end up with an offset of the grain size distribution because we are not able to detect the contribution of the finest fractions. However, since we are using a cumulative plot the slope of the remaining distribution is being preserved even if we miss the fine fraction and the gradation of the material can still be discerned from the available data. A way out of this might be the usage of more sensitive sensors for the measurement and a higher sampling frequency, but it is still doubtful if the silt fraction (particles < 0.02 mm) can be resolved in a satisfying manner.

For penetration into samples with a more uniform size distribution, e.g. single–sized diameter glass beads, the general averaged size of the grains will be matched. However, since the method is developed for a continuous size distribution, a trail of small grains will also be predicted by this method, but with a small total contribution and a very steep gradient towards the real grain diameter.

5 Application to data

5.1 UK4 sand

Having described the method and the limits of its application it is now time to apply it to cone penetrometry data. Since the bulk of the data are from penetration tests in the UK4 sand the count statistics is much better for this material than for the *Salten Skov* sand, where only a few data sets are available. The cone penetration tests were usually made in sessions dedicated to one specific material usually exchanging the penetrometer tip

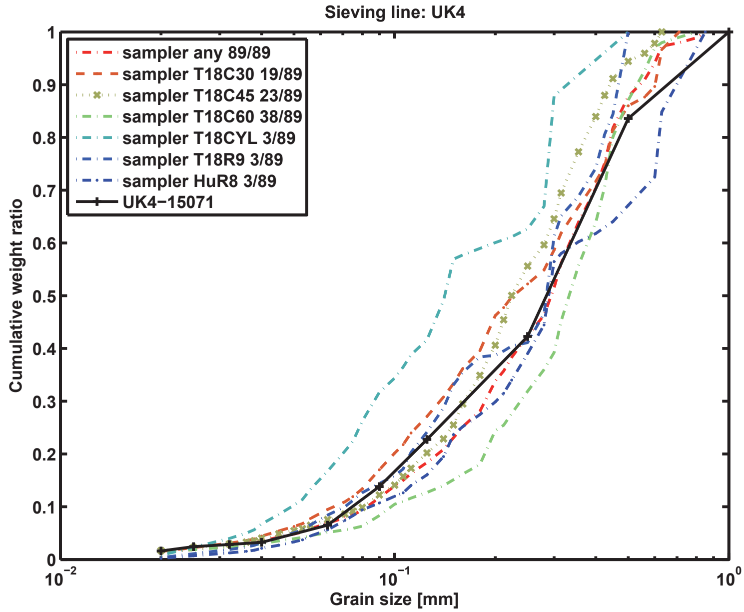

Figure 7: Cumulative grain size distribution for UK4 sand derived by using different penetrometer tips. The notation of the cone shape is typically T18XXX which means it is a penetrometry tip with 18 mm diameter and a shape indicator. C30 translates into a conical shape with 30 ° opening angle, whereas CYL and R9 denominate a cylindrical or half sphere with 9 mm radius respectively. The amount of data sets used are indicated by by e.g. 38/89 which means 38 data sets out of 89 total have been used for the evaluation.

regularly during the session. When analyzing a couple of penetration data acquired during one measurement session a quite good match to the conventional grain size distribution reference is visible.

An investigation was made to analyze the influence of the penetrometer tip shape on the result of the grain distribution reconstruction. For this purpose all available UK4 data sets were combined and a selection for the used tip was made. As can be seen in Figure 7 there seems to be no preference for a certain geometry, perhaps with the exception of the cylindrically shaped tip. However, since all of the standard tips had a certain amount of similarity a geometrical totally different tip (half sphere) was also used for comparison. This extra tip is a laboratory mock–up of the Cassini/Huygens ACC–E penetrometry sensor (HuR8), but nevertheless even here the match was quite satisfying.

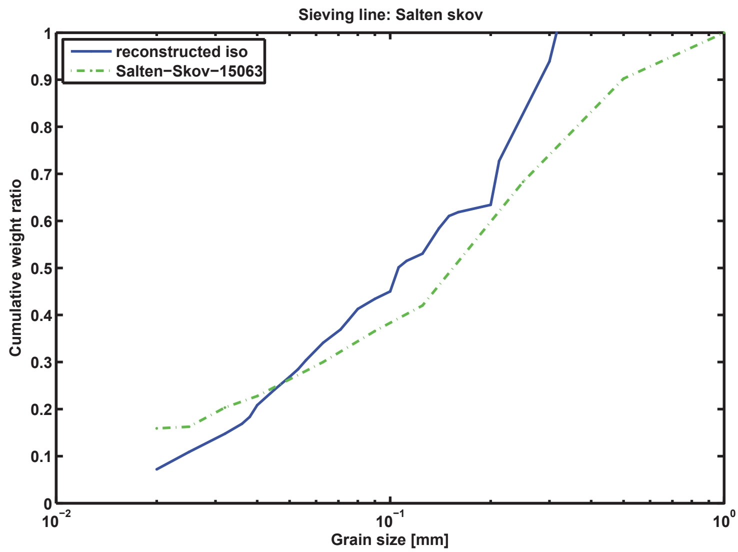

Figure 8: Cumulative grain size distribution for Salten–Skov.

5.2 Salten Skov

The other material used in the penetration tests was the Martian analogue material *Salten Skov* from Denmark. The *Salten Skov* material has a higher content of fine grains, thus the grain size distribution is less steep than that of the UK4 sand described above. Unfortunately there were only six usable data sets available for further investigation and the count statistics was suffering accordingly. On the small grains side of the distribution the error is about 5% but increases up to 30% for larger grains. As can be seen in Figure 8 the count statistics for grains above 0.2 mm is getting poor and grains above 0.3 mm are completely missed in the count.

6 Conclusions

We have demonstrated by measurements in two different analog materials that cone penetrometer measurements can not only provide knowledge on the strength of the penetrated soils, but also contain information on the grain size distribution. To extract this information, the noise spectrum of the data record must be evaluated carefully by the statistical method outlined in this paper. Since other methods (like sieving) usually used in the laboratory to determine the grain size distribution of soils and sands are often too complex and demand too heavy instrumentation to be implemented into a planetary lander payload, the method describe in this paper may become a suitable alternative, since cone penetrometers could easily be added to the standard instrumentation of surface science packages aboard planetary landers.

References

Christensen P.R., Moore H.J.: The Martian surface layer. In: Kieffer et al. (Eds): *Mars*, pp. 686–729, University of Arizona Press (1992).

Kargl G., Macher W., Kömle N.I., Thiel M., Rohe C., Ball A.J.: Accelerometry measurements using the Rosetta Lander's anchoring harpoon: experimental set–up, data reduction and signal analysis. *Planetary and Space Science* **49**, 425–435 (2001).

Kolb C., Abart R., Lottermoser W., Lammer H.: Spectroscopic survey of Mars soil analogue materials. *Internal Report* **168**, Space Research Institute, Austrian Academy of Sciences, 57 pages (2005a).

Kolb C., Martín-Fernández J., Abart R., Lammer H.: Compositional data analysis on Martian surface materials. *Internal Report* **169**, Space Research Institute, Austrian Academy of Sciences, 45 pages, August (2005b).

Kömle N.I., Ball A.J., Kargl G., Keller T., Macher W., Thiel M., Stöcker J., Rohe C.: Impact penetrometry on a comet nucleus — interpretation of laboratory data using penetration models.*Planetary and Space Science* **49**, 575–598 (2001).

Kömle N.I., Kargl G., Seiferlin K., Marczewski W.: Measuring thermo–mechanical properties of cometary surfaces: in situ methods. *Earth Moon and Planets* **90**, 269–282 (2002).

Lorenz R.D., Ball A.J.: Review of impact penetration tests and theories. In: Kömle N.I., Kargl G., Ball A.J., Lorenz R.D. (Eds) *Penetrometry in the Solar System*, Austrian Academy of Sciences Press (2001).

Lunne T., Powell J.J.M., Robertson P.K.: *Cone Penetration Test Geotechnical Practice.* Spon Press (1997).

Merrison J.P., Field D., Finster K., Lomstein B.A., Nørnberg P., Ramsing N.B., Uggerhøj E.: The Mars Simulation Laboratory, University of Aarhus. In: P. Ehrenfreund, O. Angerer, B. Battrick (Eds) *Exo–/Astro–Biology*, ESA–SP496, pp. 371–374 (2001).

Spohn T., Seiferlin K., Hagermann A., Knollenberg J., Ball A.J., Banaszkiewicz M., Benkhoff J., Gadomski S., Gregorczyk W., Grygorczuk J., Hlond M., Kargl G., Kührt E., Kömle N.I., Krasowski J., Marczewski W. , Zarnecki J.C.:MUPUS – A thermal and mechanical properties probe for the Rosetta Lander Philae. *Space Science Reviews* **128**, 339–362 (2007).

Zarnecki J.C., Leese M.R., Garry J.R.C., Ghafoor N., Hathi B.: Huygens' Surface Science Package. *Space Science Reviews* **104**, 591–609 (2002).

Zarnecki J.C., Leese M.R., Hathi B., Ball A.J., Hagermann A., TownerM.C., Lorenz R.D., McDonnell J.A.M., Green S.F., Patel M.R., Ringrose T.J., Rosenberg P.T., Atkinson K.R., Paton M.D., Banaszkiewicz M., Clark B.C., Ferri F., Fulchignoni M., Ghafoor

N.A.L., Kargl G., Svedhem H., Delderfield J., Grande M., Parker D.J., Challenor P.G., Geake J.E.: A soft solid surface on Titan as revealed by the Huygens Surface Science Package. *Nature* **438**, 792–795 (2005).

Zöhrer A.: Laboratory experiments and numerical modelling of cone penetration tests into various Martian soil analog materials. *PhD Thesis*, Technische Universität Graz, Austria, 143 pages (2006).

Zöhrer A., Kargl G.: Finite element modelling of penetration tests into Martian analogue materials. In *ESA SP*–607, P5.6 (2006).

Zöhrer A., Kargl G., Kömle N.I.: Laboratory experiments and numerical modelling of cone penetration tests into Martian analogue materials. In: *35'th COSPAR Scientific Assembly*, Abstract P2607 (2004).