# SENSING TECHNIQUES TO CHARACTERIZE LOCOMOTION ON SOILS TO BE TRAVERSED BY A ROVER

S. Michaud (1), G.A.M Kruse (2), M. Karaoulis (2), D.A. de Lange (2), M. van Winnendael (3)

(1) RUAG Space, Schaffhauserstrasse 580, 8052 Zürich, Switzerland, stephane.michaud@ruag.com
(2) Stichting Deltares, Delft, Nederland
(3) European Space Agency / ESTEC, Noordwijk, Nederland

ABSTRACT

The scientific success of rover-based exploration is a result of the rovers' capability to access diverse terrains and surface materials. Previous Mars and Moon missions based on surface mobile elements have demonstrated very well the importance and criticality of locomotion performances. Engineering expertise and modelling capabilities in the area of mobility performances are therefore important to support the rover design phase, locomotion qualification testing and ultimately mission operations planning.

Using mathematical models for this purpose implies the need to know the parameters which dominate tractive performances, and their values. However, soil conditions can vary significantly in a natural terrain, which has also been observed on Mars. Therefore not only mathematical modelling tools of vehicle–terrain interaction processes, but also specific knowledge of the relevant properties of the terrain are needed before the terrain is actually traversed.

The purpose of the ESA UNDERSTAND activity is to investigate and report the most meaningful options of techniques to characterize locomotion on soils in terrains. This study uses as much as possible the existing on-board assets for characterization of the terrain, in particular in view of the avoidance of temporary or permanent immobilization of a rover on Martian and Lunar surface.

The rover designed for the ESA ExoMars 2020 mission is taken as an example. Included in the scheme that is sketched are the necessary facilities of the rover, their functions, the data to be collected and handled, and the processing of the data and information to determine the nature of the soils in the terrain to be traversed. This work includes preliminary concept validation of two selected on-board experiments: monitoring a wheel digging into a soil and the data processing of surface temperature variation based on infrared imagery.

## 1. INTRODUCTION

The performance of a wheeled rover on granular soil is dominated by (i) the stress field in the soil under the wheel, (ii) the development of the soil-wheel interface (which is related to the wheel sinkage) during driving, (iii) unconformities in the material, such as thickness of the soil layer and soil-rock interface characteristics, iv) soil structure, particle composition (stiffness) particle size and particle shape distributions and v) porosity.

Visual analysis of observations, from orbiters and on-board cameras, of the terrain ahead of rover is very useful for path planning but has its limitations since only the very top layer is visible, while tractive performance is also influenced by the nature of the subsurface of the terrain. For obstacle detection, a highly visible aspect of terrain mobility characterization, a significant number of methods have been developed. Detection of soil conditions in the subsurface requires attention in order to obtain the insights necessary for optimizing rover design and to support the operational phase of a given mission.
The complexities of the mechanics at the soil wheel interface defy the commonly used analytical descriptions with simple soil mechanics or terramechanics parameters. A computational procedure was therefore developed earlier (the Wheel Parametric Module, WPM [3]), in which the process is described using key aspects of the forces and strength behaviour, and which allows the use of parameters derived from in situ wheel tests.

## 2. PROCESS OVERVIEW

Combinations of remote sensing techniques were found to be able to provide sufficient information to characterize soils in terrains to be traversed by a rover [5]. Parameters to estimate locomotion performance of the rover on the soils can be derived from in situ wheel tests. The overall process can be summarised as follows:

- The orbital remote sensing provides contextual information for the terrain analysis;
- Rover based remote sensing provides data, with high spatial resolution, that can be used for identification and characterization of soil covers for locomotion;
- Dedicated in situ tests with the wheels of a rover provide complementary parameters for locomotion performance prediction of the rover on the soils identified in a terrain;
- Dedicated data processing can improve the parameters used in the wheel-soil interaction formulation.

The remote sensing data can be analysed using algorithms that make use of signatures of spectral absorption, reflection and emission of the soil surface, where necessary in combination with specific terrain morphologies, such as provided by locally generated digital elevation models. Notably, analysis of rover based remote sensing of soil surface temperature variation provides information on porosity as indication for stiffness and strength, and on thickness of soil covers.
For deriving values for quantitative approximations of locomotion on the soils, use is made of in situ wheel tests on the soils, and the locomotion parameters are obtained using monitoring of facilities on board the rover.

As described in [5], two stages can be distinguished in the processing of the data from the various sensors and actuators on the rover, notably: a “learning” stage in which the discriminating values for parameters for soil type identification and wheel performance are set, and an application stage in which the observed data and discriminating values are used to support planning of the rover trajectory through a terrain. Depending the resources available on board the rover, a greater or lesser part of the computations and data storage can be handled by the rover. Therefore, on-ground data processing is proposed as baseline. Another possibility is to enhance the navigation algorithms used by the rover for that condition. This data processing and path planning optimisation process can also be supported by dedicated hardware.

## 3. REMOTE SENSING

Soil type in the terrain can be identified using data from orbital and rover based remote sensing, which are processed using a classification algorithm (where necessary supervised classification). In general, the orbital data provides large scale contextual information necessary for the analysis with the required detail which uses rover based, local, terrain analysis.
Remote sensing methods can in general be divided in the categories morphology based and spectral based. Morphology based methods (e.g. LiDAR, RADAR) provide in formation on relief, roughness and specific features of the surface, which can be an indication for type and soil layering of soil accumulations.

Soil properties like soil mineralogy, chemistry, and thermal behaviour can be detected using spectral based methods, with imaging spectroscopy sensors, infrared and visible light sensors sensing reflected and emitted radiation from the soil surface, and provide more or less direct information on the soil.

## 4. USE OF THERMAL REMOTE SENSING

Porosity and thickness of soil layers are key factors for locomotion in a terrain, as they provide basic information for sinkage and strength estimation. These key factors can be correlated to the thermal properties of soil covers, which can be obtained from temperature variation of the terrain surface [1], [5]. The radiation and thermal behaviour depend on heat capacity and conductivity, which for soils are notably dependent upon porosity and thickness of soil layer. Using thermal radiation (infrared) the spatial and temporal temperature variation of a soil surface can be observed. Variation in thermal behaviour over the course of a day and variation in the terrain due to exposure to the heating source or shadowing provides information on absorption, transport and storage of heat.

The fundamental law governing all heat transfer is the first law of thermodynamics. For a porous medium the heat transfer is derived on the mixture rule of energies appearing in solid and air (or fluid) heat transfer equations. For the solid phase the equation is expressed as:

$$\rho_s C_{p,s}\left(\frac{\partial T_s}{\partial t}\right) + \nabla \cdot q_s = Q_s \qquad (1)$$

And for the air (or fluid) phase as:

$$\rho_f C_{p,f}\left(\frac{\partial T_f}{\partial t}\right) + \rho_f C_{p,f} u_f \nabla T_f = Q_f \qquad (2)$$

Where ρ is the density [kg/m3], Cp is the specific heat capacity at constant pressure [J/(kg·K)], T is the absolute temperature [K] and u is the velocity vector [m/s]. Q contains heat sources other than viscous dissipation [W/m3].

The mixture rule applies by multiplying Eq. 1 by the solid volume fraction ($\theta_p$) multiplying Eq. 2 by the porosity (1-$\theta_p$) and summing resulting equations. It is safe to assume that u**,** is zero in most of the cases and thus is excluded from the performed simulations. Those have been done considering one type of soil and one type of rock (granite) with the properties defined in ‘Table 1’. Note that the specific heat capacity is a function of temperature.

| **Property** | **Soil** | **Granite** |
|---|---|---|
| Density (kg/$m^3$) | 2600 | 2609 |
| Thermal conductivity (W/(m·K)) | 0.0747638+1.451056E-4*$T^1$ | 0.4483333+0.004992814*$T^1$-4.32836E-6*$T^2$ |
| Heat capacity (293<T<525)(J/(Kg·K)) | 2.320236+0.01921173*$T^1$ | 2.320236+0.01921173*$T^1$ |

Table 1. The properties used for soil and hard rock simulations

With a numerical model in Comsol Mutliphysics finite element method software, the temperature of the soil surface with various thickness of soil was investigated to determine the effect of porosity on heat transfer, and possibilities to detect local terrain morphology effects. Simulation results such as given in ‘Fig. 1’ shows the development of temperature for various depths (surface up to 1.2m below surface, x-axis) for various thickness of soil (from 0cm up to 70cm of soil, overlaid above hard rock). Also the effect of differing porosities is clear in the results of simulations.

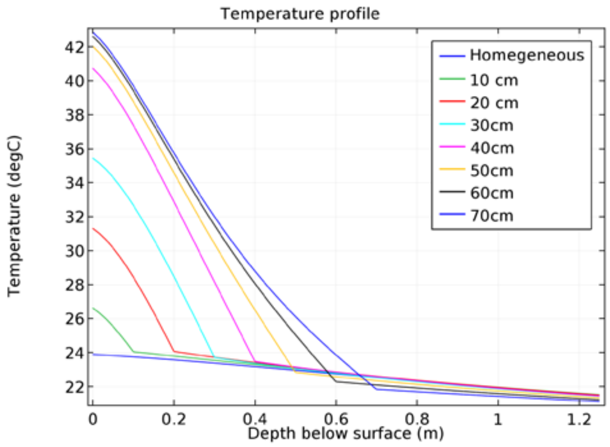


Figure 1. Simulated temperature profiles

In order to validate the outcome of the simulation, a proof of concept has been setup as shown in ‘Fig. 2’. It consists of a thermally isolated test bin with a flat bed featuring Martian soil simulant “ES3” (without gravel), a radiative heating source, an infrared thermal camera and a thermal sensor located 10cm below soil surface for the purpose of validating the simulations.
The isolation accommodated on the bottom of the bin and side walls is made of stiff 5cm wide aluminium coated polystyrene panels with a typical thermal conductivity of 0.03 W / (m K).

In the bin, two concrete plates as shown in ‘Fig. 2’ with dimension 500x500x40mm each and a weight of 23.8kg (2380 kg/m3) are accommodated at various heights. The plates are clean and have low roughness allowing proper thermal conduction between them. The estimated thermal conductivity is 1.5 W / (m K).

Figure 2. Set-up for measuring thermal variation with various thickness of soil layer

The tests consisted of heating the soil with the radiator up to an abrupt stop, simulating a shadow cast by the rover or the night phase. After four hours heating, the soil surface temperature was at approx. 61°C, for all experiments. The cooling phase is very similar in all experiments with the exception of the smallest 10cm soil layer. Fig.3 shows the temperature decrease between about 10 min. and 20 min. for soil depths 10cm (black), 30cm (blue), and 40cm (red).

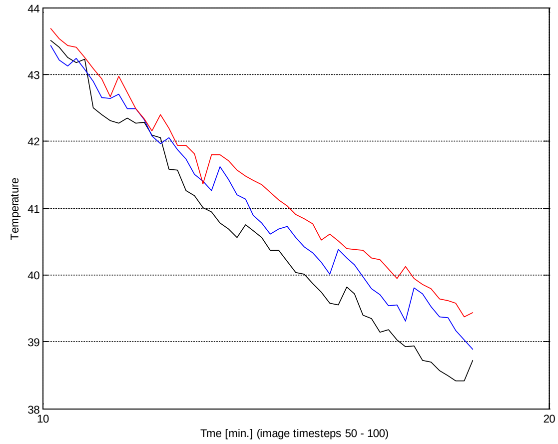


Figure 3. Maximum temperature from thermal camera for various thickness of soil between 10 and 20 min

The difference in effect of soil depth on temperature development is consistent with the findings of simulations. It is therefore to be expected that using such simulations the heat conductivity and the heat capacity of the used soil and concrete slab set up can be approximated using reverse analysis.
Soil characteristics relevant for locomotion can be derived using reverse analysis of the temperature change over time together with general information on mineralogical composition, and details of terrain morphology. This estimation of soil porosity and thickness of soil layer is to be performed based on correlation between porosity and thermal properties, and subsequent thickness estimations using the temporal temperature profile.

The reverse analysis can be performed with the commonly available numerical models which allow incorporation of detailed conditions and properties of the soils, layering, and the atmosphere involved. Computationally far less demanding analytical procedures are available for simplified conditions, which can be used for estimating soil properties in the surroundings of the rover with very limited resources.

Learning techniques correlating effective rover slip ratio with thermal inertia are discussed in [1]. Similar methods in combination with the information from in-situ single wheel tests can be used to model locomotion performance of the specific wheel on the specific soil type.

For the ExoMars mission remote sensing can be performed based on images and areal scans from PanCam and potentially using the navigation cameras (LocCam and NavCam). Soil porosity and, where relevant, soil cover thickness estimation at selected sites is derived using data from rover based thermal remote sensors to track temporal temperature changes upon natural or rover-induced shadow provided temporal variation in solar radiation.

## 5. STAGNANT WHEEL TEST

Various estimation procedures for values of soil mechanical and terramechanics parameters have been published [2]. The behaviour of a moving wheel on soil involves very large strain, stress gradients, and strain rate differences, and depends very much on the nature of the soil and the geometry of the wheel and the load. These conditions require very detailed and computationally very demanding numerical methods and values for a range of specific parameters for realistic simulation. Less demanding analytical models are also available, but depend on specifics of soils and wheels. In situ determination of wheel performance on a specific soil can be used to derive input values needed by these analytical models in order to predict locomotion performance. The use of in situ tests was therefore investigated in the ESA UNDERSTAND activity.

In general, the trafficability of a soil is considered adequate for a given vehicle if the soil has sufficient bearing capacity to support the vehicle and sufficient traction capacity to enable the vehicle to develop the forward thrust necessary to overcome its motion resistance. The most common method for determining thrust capability is to determine the wheel drawbar pull (i.e. the difference between traction and motion resistance) at a given slip ratio. The thrust is influenced to a large extend by the sinkage of the wheel in the soil. Determining the sinkage for a soil and a moving and slipping wheel is however non trivial.

On the current ExoMars rover, there is little possibility to create an external force representing the drawbar pull. Motion on slope using gravitational resistive force is a possibility that is limited due to difference in soil type and conditions on uneven terrain. An attempt based on controlling rover wheels at different angular velocities has been explored within the project. Analytical results are promising but would need to be confirmed with rover level experiment.

Therefore concept discussed here is based on having a stationary rover while only one or two wheels are rotating. The main advantage is that wheel load and interfaced soil remain constant. Moreover the determination of rover velocity is not necessary as long as the in plane displacement remains marginal compared to the wheel rotation. The data to be recorded for on-ground processing are the wheel sinkage and input torque. In addition, the wheel load is to be established based on the rover state.

The concept was developed using the WPM [3], for which the relevant part is summarized here. Figure 4 is a sketch of the forces involved in the locomotion. Magnitude and direction of the normal force vector of the soil-wheel contact during locomotion, are key element in the WPM, together with the mobilized friction, which characterizes the strength of the soil for a moving and slipping wheel.

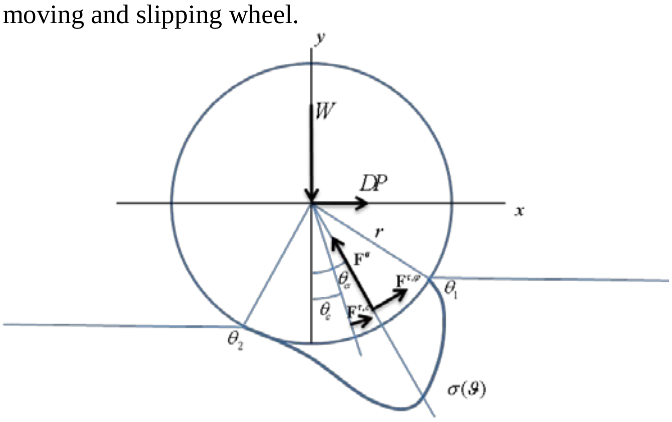


Figure 4. Sketch for the analysis of the interaction between a wheel and deformable soil during driving as used in the WPM [3].

In the WPM the drawbar pull, normalized for wheel load is derived to be:

$$\frac{DP}{W} = \tan\left(\varphi_{mob} - \vartheta_{\sigma}\right) \qquad (3)$$

with $DP$: Drawbar pull, $W$: wheel load, $\varphi_{mob}$: mobilized friction, $\vartheta_{\sigma}$: angle of normal force.

As described in [3] the mobilized friction is related to the torque and angle of the normal force as in:

$$\tan\varphi_{mob} = \frac{T\cos\vartheta_{\sigma}}{r_{eq} f(s)W - T\sin\vartheta_{\sigma}} \qquad (4)$$

with $T$ as torque, $\vartheta_{\sigma}$ angle of the normal force, $r_{eq}$ radius of the wheel. $f(s)$ is a factor function of wheel sinkage that can be approximated to 1. However deviation from 1 becomes more important at high sinkage and depends also on the wheel type.
In [3] the angle of the normal force has been crudely approximated by a direct relation to the sinkage, namely:

$$\vartheta_{\sigma} \approx a + b\vartheta_1 \qquad (5)$$

with $a$ and $b$ parameters which can be determined from a fit, as was done for a for a range of soils in see [3], and $\vartheta_1$ determined by sinkage.

The torque together with information on the sinkage and information on the wheel load can provide the mobilized friction parameter, directly or indirectly as discussed hereafter.

## 1.1. Wheel Torque

In the absence of a torque sensor, the wheel input torque is to be derived from motor current. Energy balance has been used in [2]. Such method requires an in-situ "no-load" characterisation test and has been evaluated in the proof of concept. This provides a worst-case accuracy of 13% under similar thermal conditions. Such method is therefore recommended for rover having the capability to run this characterisation test. During the ExoMars deployment phase it seems an opportunity exist for conducting such a test when the wheel is off-loaded. During the mission, it will be significantly more challenging to lift up a wheel.

The other method is based on using the actuator current to torque relationship based on datasheet data or characterisation test. The disadvantage is that this relationship and in particular the efficiency varies over time and is sensitive to thermal conditions. Such method has also been evaluated to estimate wheel torque with 10% accuracy at beginning of life (BoL) and under the same thermal conditions. The test results, including reference value from an accommodated torque sensor are shown on 'Fig. 5'.

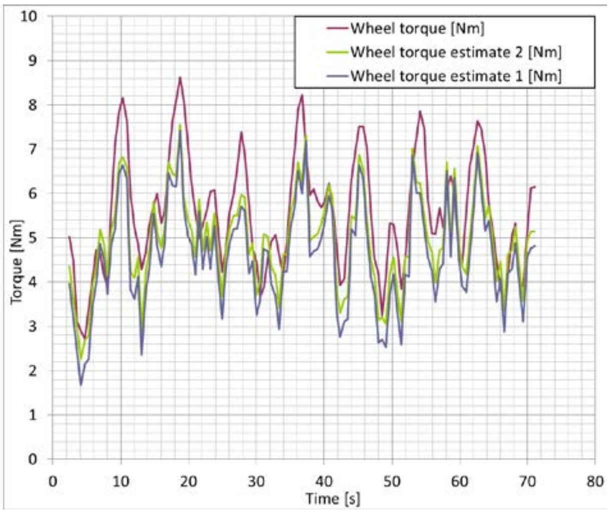


Figure 5. Wheel torque estimates test

The torque measured in the stagnant wheel test can be used to directly estimate the drawbar pull of the wheel on the soil as shown in Figure 6. The good linear correlation between load normalized torque and drawbar pull in the proof of concept was also found to be present for all 4 soil simulant materials used in the ESA SWIFT and EXPERTISE activities [3], [4]. There are only minor changes in the trend for the 4 soil simulants as can be seen in 'Fig. 6'.

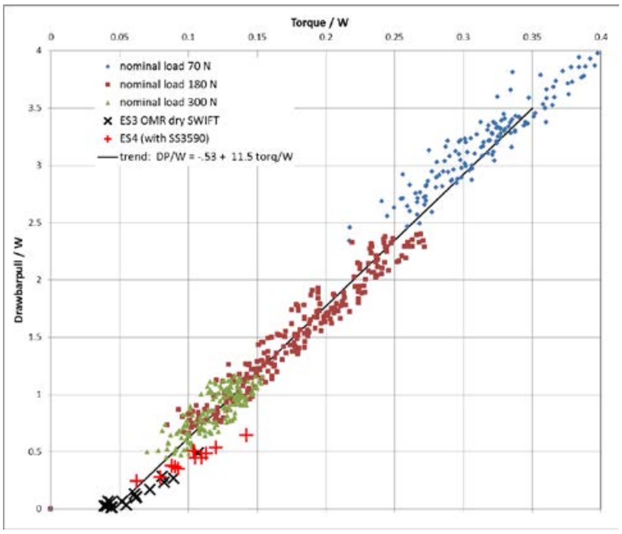


Figure 6. Graph of the correlation between torque, T, and drawbar pull, DP, both normalized after the load, W, for the 100% slip tests in UNDERSTAND, and single wheel tests in SWIFT and EXPERTISE [3], [4]

A more universal application of the results of the stagnant wheel test is the use of a soil strength characteristic, which can be derived for the combination of the wheel and soil, and which does not depend upon sinkage. The parameter is named M here, and is given as:

$$M = \frac{T}{W * l'} * \left(\frac{W}{W_{ref}}\right)^{\frac{1}{2}} [-] \quad (6)$$

with: $l'$ the projected length of the embedded wheel circumference on the initial soil surface and with $W_{ref}$=100 N.

The value of the parameter can be determined from torque and wheel load in a stagnant wheel test as shown in Figure 7.

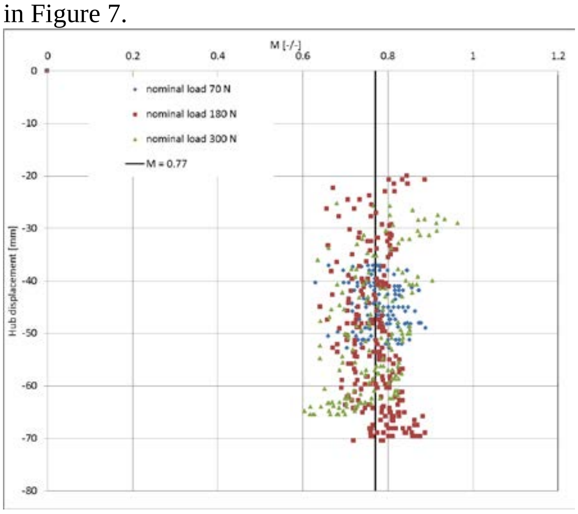


Figure 7. Graph of the sinkage and values for the parameter M (as per 'Eq. 1') derived from the 100% slip single wheel tests.

The value of M is approximately 0.77 for the ES3-SS3590 soil simulant [5]. The parameter M can be used as strength characteristic for the WPM and, with adaptation, in other analytical terramechanics approaches.

## 1.2. Sinkage

The sinkage is directly relevant for soil influences on ground clearance. Sinkage is also a most important aspect of soil-wheel interaction, as it among others determines the angle of the normal force (see ‘Fig. 4’).

Hub displacement cannot be directly measured with sensors on-board the ExoMars rover. The level of penetration of the wheel rim in the soil, the sinkage, is even more difficult to establish for flexible wheels. For the ExoMars mission, hub displacement based on image analysis from PanCam in combination with the RIM is proposed to be monitored together with rover position and BEMA orientation using the navigation sensors.

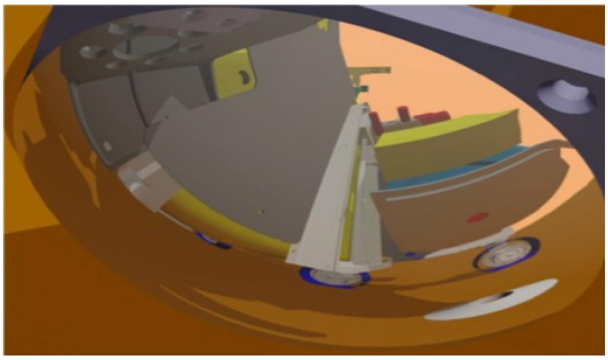

Figure 8. PanCam estimated view using the Rover Inspection Mirror (RIM)

Using the ESA EXPERTISE test data [4], the hub vertical displacement and sinkage relationship are reported on ‘Fig. 9’ for the ExoMars phase B2 flexible wheel on soil ES4-SS3590+MS6.

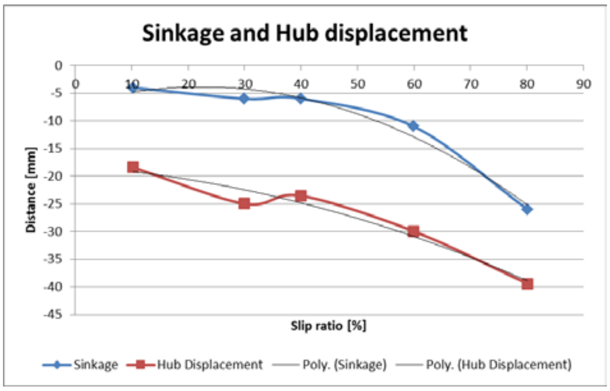


Figure 9. Sinkage and hub displacement of the ExoMars phase B2 flexible wheel as a function of slip ratio [4]

Using the measured wheel radial stiffness, for the lower wheel load of 70N, the wheel deflexion will be between 4.7 and 5.1 mm. The measured difference between sinkage and hub displacement is 4.9 to 9 mm. In this lower range the measurement accuracy is considered to be of a few mm and therefore the measured wheel deflexion is considered very similar to the derived one.

Under 300N load on a rigid base, the wheel deflexion will be between 20 and 22 mm. The measured difference between sinkage and hub displacement is 14 to 19 mm on the tested soil. This lower measured wheel deflexion shown in ‘Fig. 9’ is expected due to the nature of the soil that does not behave exactly like a rigid material. Based on this knowledge, a corrective factor for a given soil type and relative density can be established bringing the conversion accuracy from hub displacement to sinkage to within a few mm.

Calculation methods for sinkage produce only very rough estimates so far, and thereby seriously limit estimation of locomotion on soil. For the WPM [3] a tentative slip sinkage formulation is used that is based on the observed sinkage in the experiments on all 4 soil simulant materials used in SWIFT and EXPERTISE.
The formulation has been validated up to about 80% slip and would need to be confirmed for the current experiment at 100% slip ratio:

$$z_s = \left(z_1 - z_0\right) s^2 + z_0 \qquad (7)$$

with: $z_s$ sinkage at certain slip ratio, $z_1$ maximum sinkage.

The proof of concept provides evidence that a polynomial interpolation of degree 2 is also sufficient to accurately determine the trend line of the slip sinkage in the stagnant wheel test (see ‘Fig. 10’). This measurement during the stagnant wheel test can give soil and wheel specific information for sinkage.

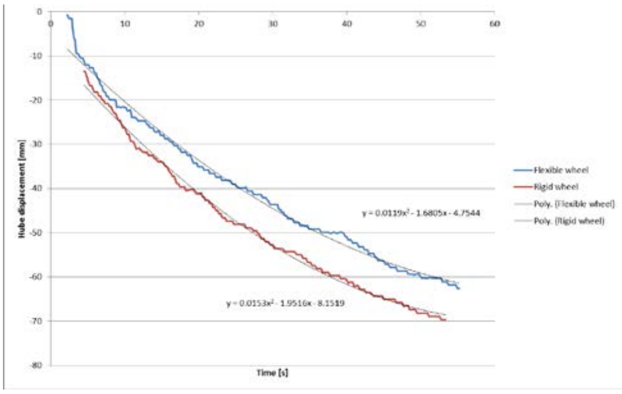


Figure 10. Sinkage measured during experiment for the ExoMars phase B2 flexible wheel and a rigid wheel of same diameter

Figure 11. ExoMars phase B2 flexible wheel on Martian soil simulant ES3

## 6. MISSION OPERATIONS PLANNING

For rover mission operation, a database can be established with soil properties for identified soil types which are stored in a GIS specifying the soil and terrain types occurrences in the terrain. The visual and infrared (IR) signatures refer to peaks and other features in spectrograms, which are related to notably mineralogy. The characteristics of the morphology refer to features such as dunes, stones, or presence or absence of hard rock features such as joints and other discontinuities. Such work can be integrated in a simulation environment by superposing the soil map to a digital elevation map as shown on 'Fig . 11'.

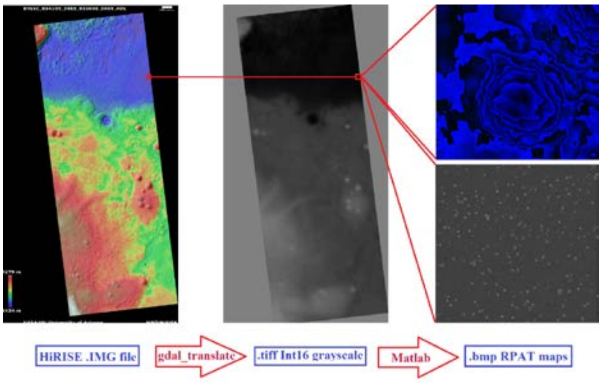

Figure 12. Example of map making process flow

## 7. CONCLUSION

The reported activity deals primarily with the collection of characterization data from on-board sensors of rovers for the purpose of detecting soil conditions to improve trafficability on a roving vehicle.

The first method used in the UNDERSTAND project is based on the use of the wheel-soil interaction formulation as per the Wheel Parametric Model resulting from the ESA SWIFT project, but can also be used for other models describing the intricate interaction of wheels with soil, including estimation of parameters for the Bekker-Reece approach, which is helpful for compatibility with the commonly referred to terramechanics models.
The method to obtain locomotion parameters and their values is based on in situ monitoring wheel torque and sinkage. A stagnant wheel test, in which the rover is stagnant while one or more wheels rotate, was found promising for the value of information obtainable as well as in terms of execution of such tests with the ESA ExoMars rover. The in situ stagnant wheel test was found to provide pertinent data for determining locomotion performance for a wheel on a soil.

The second method is based on the relation between thermal properties of different soil types and soil layer thickness and uses collecting and analysis of thermal images. The surface temperature variation provides information on heat capacity and conductivity of soils, which are in general determined to a large extent by porosity and thickness of soil covers. Since porosity provides for a first approach on soil mechanical behaviour, variation of locomotion characteristics of soils can be derived from thermal images.
The rover based remote sensing can provide sufficient detail on the terrain surface to overcome limitations in analysis of temperature data encountered with orbital remote sensing data. Test using available soil simulant materials to verify results of numerical computations on soil surface temperature variation for varying porosity and thickness of soil covers, and of rover based remote sensing facilities can identify the possibilities and limitations of the method. Currently only the variation of the thickness of a layer of one soil type has been validated during a dedicated experiment. Elsewhere additional information on the use of thermal properties for locomotion performance has become available recently [1].

The execution of the discussed on-board experiments is considered feasible on Mars with the ExoMars rover and can serve the planning of current and future missions by increasing the accuracy of predictive tools and the rover capability to access safely even more demanding area.

Offline analysis of the data is necessary in order to establish a soil strength parameter, and the relation between torque and hub displacement for the wheels of the rover on the soil. The estimation of drawbar pull versus slip for a moving wheel (i.e. full range of slip ratio) is not trivial to be determined. This can be done using (i) the known relations between torque and drawbar pull for the soil type, or (ii) a soil strength parameter M discussed in this paper, or iii) using a complementary in-situ test by monitoring slip and torque for all wheels, notably while adapting the slip value for one or more wheels. Using the torque and sinkage information from all 6 wheels of the ExoMars rover, the mobilized friction of the soil can be determined using the equations for the Wheel Parametric Model (see [5]).

## **8.** REFERENCES


1. Cunningham, Chr. (2017). *Improving Prediction of Traversability for Planetary Rovers Using Thermal Imaging*. Robotics Inst. Carnegie Mellon Un., Pittsburg PA, 138 pp.

2. Sullivan,R. (2011). Cohesions, friction angles, and other physical properties of Martian regolith from Mars Exploration Rover wheel trenches and scuffs, Journal of geophysical Research, Vol. 116, E02006, 2011

3. ESA, RUAG, Deltares (2014). *Parametric Tool Design Description*, ESA project SWIFT, phase 2, TN12a. Deltares report 1204498-003 version 2 for RUAG and ESA, 68 pp.

4. ESA, RUAG, Deltares, (2014). MREP EXPERTISE *Evaluation of Wheel-Soil interaction test data*. RUAG report MREP-TNO-RSSz-008 issue 1, 30 pp

5. ESA, RUAG, Deltares (2017). *Conceptual design Description*, ESA project SWIFT, phase 2, TN12a, 91 pp.