



# Electronically Assisted Surveying on Plain Track and Switches with GPS Link



The measuring system EM-SAT (electronic track surveying car with satellite) has proven itself in practical operation since 1990 [1]. Six EM-SAT are now in operation on DB Netz AG, three EM-SAT (Fig. 1) on ÖBB and one EM-SAT on FS tracks. Seven EM-SAT will be put into operation by DB Netz AG in 2001.

On the work sites in 1998 and 1999, especially on high-speed tracks, deviations of the reference points of up to 25mm were found (in part on tracks with a mast spacing of 60 meters). When the EM-SAT design received official registration, the much higher accuracy of the EM-SAT in comparative measurements (Fig. 2), compared to the manual and optical method, was documented.

Mechanised surveying with the EM-Sat allows cost savings of 3 Euro per recorded metre in comparison to the traditional manual and optical method. In addition, the output of the tamper is increased by 50% on plain track, as it is not necessary to bring forward the laser unit and the start and end points for tamping are already predetermined.

The automated, computer-assisted surveying technique EM-SAT (Fig. 1) measures long wave track faults in longitudinal level and curvature (alignment) and calculates precise control values for the tamping machine. The procedure is described in DB guideline 824.0520. This guideline was elaborated by DB AG following extensive practical operations and finally adopted on May 1<sup>st</sup> 2000.

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Fig. 1: EM-SAT in operation



Fig. 2: Comparative values at the design registration

Additional evaluation dated 3.8.1999 for the mean values & standard deviations of manual measurements							
Distance measurements to the fixed point							
	Actual measurements FPM			Actual measurements manually			
	Mast	1st measurement	2nd measurement	3rd measurement	Mast	2nd measurement	3rd measurement
77/27		2574	2573	1	2555	2578	-23
78/3		3598	2600	-2	3586	3600	-14
78/7		3433	3434	-1	3439	3438	1

Longitudinal level	
2 rows of measurements	
$n$	= 79 (number measured values)
$\Delta\bar{X}$	= 1,04 mm (mean value)
$\sigma$	= 0,93 mm (standard deviation of differences)
$\Delta X \text{ max}$	= 4 mm (max. single fault)
$\sigma_{\text{EMSAT}}$	= <b>0,3 mm</b>

Versine	
2 rows of measurements	
$n$	= 79
$\Delta\bar{X}$	= 0,9 mm
$\sigma$	= 0,84 mm
$\Delta X \text{ max}$	= 3 mm
$\sigma_{\text{EMSAT}}$	= <b>0,2 mm</b>
$\sigma(1)$ - expected maximum fault at $3 \cdot \sigma$	

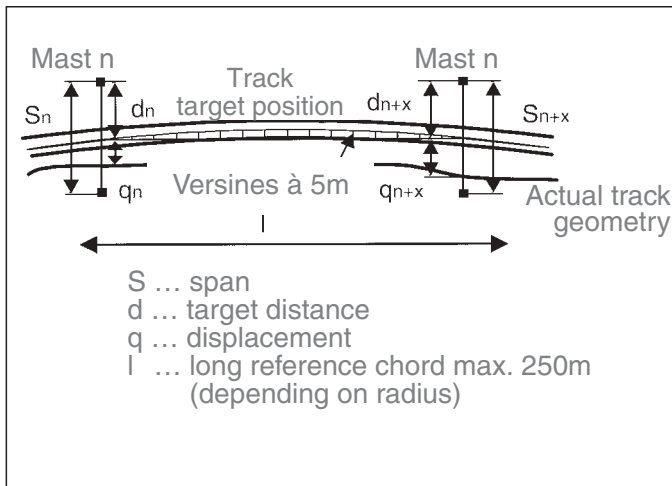


Fig. 3: Sketch definition of the marked track

The EM-SAT is an auxiliary vehicle available either in a two axled version or in a bogie version. For the actual surveying, the vehicle carries a separate satellite equipped for self-propulsion by an electric motor. The laser transmitter with a modulated laser diode is mounted on the satellite. The vehicle moves under its own power in either direction with a maximum speed of 100 km/h (single axle version) or 120 km/h (bogie version). The measurements are performed from secure working positions, i.e. from the main vehicle and the satellite, so there is no need be on the service track during measuring.

After the satellite is separated from the

The EM-SAT is used for:

- ▷ planning and determining of tamping and lining sections,
- ▷ surveying prior to tamping work according to DB guideline 824.3010,
- ▷ surveying for elimination of spot faults using a spot fault tamper,
- ▷ recording of track renewal (verification of the track bed structure in respect of longitudinal level and alignment) before and after the tamping runs,
- ▷ acceptance of new track to identify possible long wave faults.

The EM-Sat continuously determines – above all – long wave faults in longitudinal level and curvature (alignment). Figure 3 shows the definitions of the reference chord and the fixed points of the marked track. The actual values obtained are compared to the target values, recorded (analogue print) and transmitted to the tamping machine for further use.

Long wave faults in the sense of this guideline are geometry faults in longitudinal level and curvature (alignment) with greater wavelengths up to 250m.

The comparison of the actual with the target values is made at all marking points by means of the fixed point measuring system (Fig. 4).

The benefits of EM-SAT measuring compared to manual surveying are:

- ▷ high measuring accuracy and measuring speed,
- ▷ measuring and identifying long wave faults based on the lengthened reference chord,
- ▷ identification and possible elimination of changes in position and height of existing markings,



Fig. 4: Fixed point measuring device

- ▷ high data reliability from recording with the measuring instruments to the data evaluation and transmission to the tamping machine, due to the absence of data interruption (continuous data flow),
- ▷ personnel at safe workplaces to avoid dangers from passing trains.

main vehicle and set up on the track, the measurements are taken in a cyclic sequence consisting of the following steps:

- ▷ The main vehicle is set up at the first reference point directly above the first vehicle positioning marking (colour code on the inner side of the rail – positioning via video camera).
- ▷ The satellite is moved forward to approx. 8-10 m beyond the next reference point, up to a maximum 250 m.
- ▷ The laser beam is aimed at the xy-laser receiver camera of the main vehicle.
- ▷ The measuring run of the main vehicle towards the satellite is carried out with a speed of  $V_{meas} = 5-7$  km/h.
- ▷ Final measurement is carried out at the reference marking in front of the satellite car and the main vehicle is braked.
- ▷ The satellite travels to approx. 8-10 m beyond the next reference point and the next measuring run begins as previously described.

## Description of the track surveying car EM-SAT

The EM-SAT determines:

- ▷ alignment and longitudinal level based on the longer measuring basis (laser reference chord),
- ▷ superelevation and cross-level by means of an inclinometer,
- ▷ distance between fixed points by means of a measuring wheel,
- ▷ track gauge by means of a telescopic measuring axle.

The range of application and the measuring accuracy are the following:

Range of application:

- ▷ Versines of the alignment: max. 1000 mm
- ▷ Versines of longitudinal level: max. 400 mm
- ▷ Laser chord length: max. approx. 250 m
- ▷ Measuring performance: 1.5–2.6 km/h, depending on the length of the laser chords.

Measuring accuracy:

- ▷ Versines: 1 mm repeatability
- ▷ Cross level: 1 mm mechanical response accuracy
- ▷ Track gauge: 1 mm mechanical response accuracy
- ▷ Distance measurement: 0.1 m / 100 m

In addition, the EM-SAT is equipped with an 8 channel recorder and a geometry measuring system (measuring chord with mechanical measuring axles). Using this additional measuring and recording equipment, the documentation of the track geometry can be established according to guideline 824.3010 in similarity to tamping machines.

### Description of the fixed point measuring device

For the exact definition of the absolute track position, i.e. for the determination of the displacement and lifting values in the area of the marking points (bolts, low points, masts, etc.), a fixed point measuring device is currently used (Fig. 4). This device is a combination of an electronic speed indicator for infra-red distance measurement and goniometers together with a precision inclinometer for measuring the superelevation. The trolley is built in lightweight aluminium design and can easily be taken apart into three pieces. It can thus be transported by any standard motor car and operated by one man. For the storage and evaluation of measuring data, the device is equipped with a micro-controller, a report printer and a data memory card.

To determine the displacement and lifting values (measurement), the fixed point measuring device is positioned on the corresponding marking and immobilised with quick-release fastenings on the

predetermined datum rail. For the measuring, a prism is placed on the marked point. The actual and target values are stored on the memory card and read into the main computer of the EM-SAT for the calculation of the actual vs. target differences. In addition, a target vs. actual comparison in level and line (lifting and displacement) is shown on the display and a control strip is printed out.

The range of application and the measuring accuracy of the fixed point measuring device are the following:

Range of application

- ▷ Line measuring unit:  $\geq 1.3$  m
- ▷ Measuring performance: 1.1-2.6 km/h depending on the distance between the marking points and the work to be performed (actual track geometry/span)

Measuring accuracy

(for the individual measurements according to the manufacturer in close range)

- ▷ Height measurement: 1-3 mm (1.5-5 m)
- ▷ Line measurement: 1-3 mm (1.5-15 m)

### Use in switches

The EM-SAT and the fixed point measuring device can be used for surveying switches and switch connections, relative to the outer marking.

Special attention reads to be paid to the following:

- ▷ The allocation track and the opposite direction track or the diverging track must be measured from the same marking points. In a switch connection, the measuring length — laser reference chord length — must overlap at least the area from one switch axis to the other switch axis.
- ▷ The actual distance between centres of lines should be measured additionally at the end of the switch using the fixed point measuring device.
- ▷ On switch connections, consistent markings need to be chosen for the entire junction, i.e. the same marking points need to be chosen for the allocation track and the opposite direction track. Also, the junction area (switch axis to switch axis) must be within one measuring distance. The

target values must be read into the computer system accordingly.

- ▷ The switch connection itself should be recorded using the beginnings and ends of both switches, additional mobile chords and if possible a fixed laser chord.
- ▷ Verification of the length of the adjusting pieces between the ends of the switches.

### Use of the EM-SAT for track and switch relaying work

The EM-SAT is also used for track relaying, the described measurements are then carried out immediately before the tamping run. It is important that the lifting and lining values determined by the EM-SAT for the individual tamping runs result in a parallel longitudinal level of the projected target condition. This is achieved by limiting the given values for the lifting process according to DS 820 03 02 or by treating the settlements of the track prior to the combined first lifting and compacting run. Optionally the EM-SAT can be equipped with a radio data transmission system, allowing the wireless transmission of the data to the automatic geometry guiding computer WINALC of the tamping machine.

### Definition and pre-conditions for the measuring work prior to maintenance

In the case of maintenance work — excluding renewal work — the customer determines where measuring needs to be performed with a longer measuring chord to safely eliminate long wave faults by evaluating the data originating from:

- ▷ the track geometry measuring runs,
- ▷ the technical running tests,
- ▷ and other inspection results, if available.

Except for renewal work, the measuring is planned in such a way that it is completed eight weeks before the maintenance work is due to start, so the necessary operational and preparatory steps can be scheduled and work can be commenced in a timely manner (for instance ballasting for larger lifts, rail cutting for large displacements, etc.).

## Evaluating the measuring data and determining the steps to be taken

The contractor hands over the computer-generated scaled graphic recording (measuring chart) (Fig. 5) of the lifting, displacement and cross-level values to the permanent way district so that the necessary steps can be identified. Technical advice is given by the EM-SAT operator. After an evaluation, the permanent way district chooses start and end points for the tamping in such a manner that a harmonious transition to the

untamped sections is achieved both in longitudinal level and in curvature (alignment).

On high points a zero lifting is acceptable, if the displacement in this area is only minimal and the deviation of the cross-level is less than 5 mm. The cross-level is then ramped up at 1:2000.

### Handing-over and storage of the measuring documents

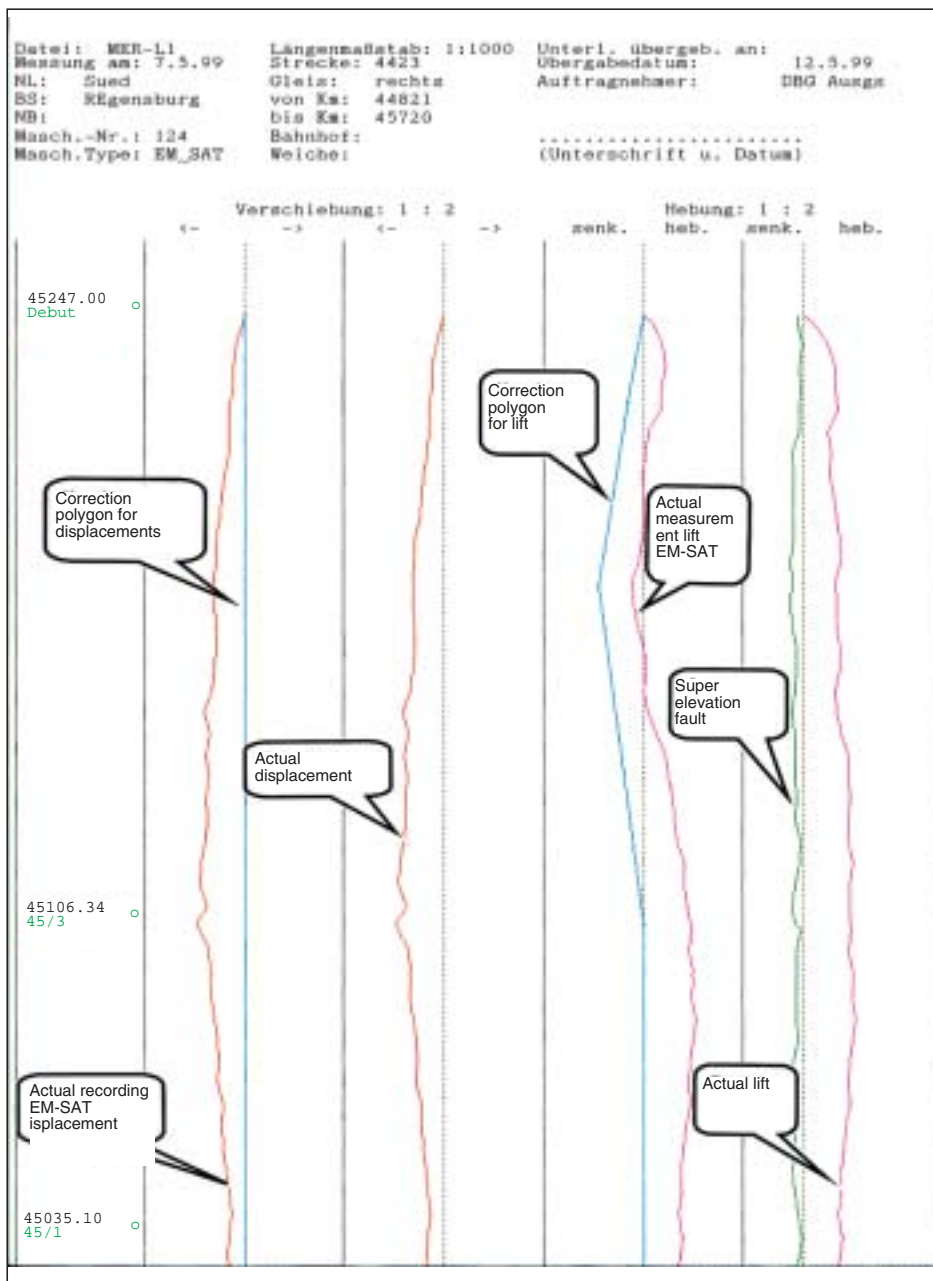
The tamping contractor receives the target geometric values, the lifting and displacement values, as well as the target

spacing and target height values of the reference points in electronic form (on a floppy disk for example). The contractor is also given a digital print of the lifting and displacement values that can be used, if necessary (in case of a computer failure on the tamping machine) to manually guide the tamping machine.

The print-out data is used to:

- ▷ determine the length of the tamping sections,
- ▷ select the appropriate lifting and lining values to identify the start and end points of the tamping run,
- ▷ identify the cross-level, especially at the start and end points of the tamping run,
- ▷ determine the ballast needed,
- ▷ determine the need for specialists in the field of track security and electrical engineering.

The measuring results must be recorded after each measuring/processing step by graphic and electronic means (a floppy disk, for example). The contractor will mark the graphic documents with the information in respect of location and order and they will be stored at the permanent way district. The permanent way district has a "mini track-surveying-software" to be able to access the files.



## Use of GPS for track maintenance work

A new trend in track maintenance is the use of the Global Positioning System (GPS). Geo++@GNBAHN is a system for kinematic track measuring [2 and 3]. It allows the complete recording of the track geometry, i.e. the three-dimensional track co-ordinates, the superelevation as well as the track gauge with high accuracy and high spatial density in one operation in real-time. GNBAHN was developed in co-operation with DB Netz AG and has already been used successfully on many tracks of the DB Netz AG network.

## Range of application

GNBAHN is suitable for all tasks requiring accurate surveying of the track geometry. These include:

Fig. 5: EM-SAT track correction diagram

- ▷ quality control after track laying and renewal,
- ▷ peeping-out a track,
- ▷ measurement of target geometry and of actual measured geometry.

The GNBAHN/PM software serves to record, control and visualise all measuring data as well as technical track calculations with a graphic operator interface.



Fig. 6: Satellite trolley with GPS measuring device

## Combination of EM-SAT and GPS

From 1993 to 1995, the Technical University Graz and the Research and Testing Department of Plasser & Theurer studied in a joint research project the possible uses of GPS for track surveying [2]. The objective was to answer the question whether GPS could achieve a similar accuracy to laser reference chord measuring methods. The answer to this question was definitely negative [3 and 4]. The highest absolute alignment accuracy achievable with GPS is approximately  $\pm 6$  mm. The accuracy in level is worse by a factor between 1.5 and 2. GPS is not precise enough to be used instead of a laser reference chord measuring system. The requirements in terms of track correction values to guide tamping machines are about 1mm.

The errors in GPS measurements are influenced by the following parameters:

- ▷ ionospheric refraction,
- ▷ tropospheric refraction,
- ▷ phase noise,
- ▷ number of satellites received,
- ▷ configuration of receivers and satellites, as well as
- ▷ multipath effects.

The ionospheric refraction can be compensated by using dual-frequency receivers. The tropospheric influence can be reduced by the respective model calculations. The phase noise depends on the quality of the chosen satellite receivers. The number of satellites received depends on the topography, but can be improved by using multi-system receivers (simultaneous reception of the satellites of the Navstar and Glonass systems). The configuration of the receivers and the satellites varies over time (satellite orbits) and depends on the geographic location and can hardly be influenced (except for planning the measuring during certain hours of the day).

The multipath effect has the most significant influence on the error levels. When multipath effects occur, not only is the phase position signal received, but also a reflected signal (from roofs, rolling stock, etc.). The reflected signal is superimposed on the original signal and leads to erroneous measurements. Multipath can be reduced by using special antennas and kinematic measurements, but unfortunately it cannot be completely eliminated. Most of the time, the special antennas (choked ring antennas) can only eliminate ground reflections, i.e. signals with a small height angle.

With the EM-SAT mechanised measuring of long chords has become reality. The absolute accuracy of EM-SAT measurements is better than 1 mm. To determine the chord position and hence the actual and target track geometry in a co-ordinate system, fixed points are necessary. The draw-back of fixed points is their inconstancy (in an absolute sense, they are not "fixed"), they are complicated and expensive in terms of measuring work and maintenance, and they slow down the work progress of mechanised systems.

GPS provides an elegant method of replacing fixed points. The achievable accuracy in line of  $\pm 6$  mm and  $\pm 9$  to 12 mm in level is fully sufficient for these purposes.

The calibration of a fixed point (spacing and height) using span measuring methods induces costs of € 130,- (plus track safety costs) per measurement. This clearly demonstrates the savings potential of the combined use of EM-SAT and GPS, that can still be achieved.

### Requirements for high accuracy GPS measuring

- ▷ Reception of at least four satellites simultaneously.
- ▷ Relative GPS-measurements (1 fixed

GPS reference receiver and 1 moving GPS receiver as a rover).

- ▷ A fixed GPS reference station (distance of 4 to 6 km – for example calibrated reference points in train stations or on buildings or GPS reference networks currently being built). DB Netz AG is planning to build a reference network with basic distance of 4 km (that implies a maximum distance to the reference station of 2 km).

### GPS problem areas

- ▷ Reduced satellite reception (topography, buildings, bridges, tunnels, etc.),
- ▷ Multipath reception.

### Actual level of implementation

An EM-SAT equipped with a GPS measuring device is currently under test operation on the Austrian Federal Railways. The EM-SAT delivered in April 2000 to Krebs in Germany is also equipped with a GPS measuring device.

Fig. 6 shows the EM-SAT satellite trolley with a GPS measuring device. A GPS antenna is mounted on the side of the self-propelled satellite. The antenna's exact geometric position relative to the wheel points touching the rail is calibrated and recorded. Additionally, the satellite trolley is equipped with a GPS receiver of the latest generation (simultaneous reception of Navstar and Glonass satellites), which is linked to a computer for data recording. The program for kinematic track measuring GNBAHN is installed on the computer. The satellite trolley is equipped with a non-contact gauge measuring and superelevation measuring device, so the antenna's position relative to the rail is known at all times. The main vehicle is fitted with the non-contact distance measuring unit Distomat, which accurately measures the distance between the satellite trolley and the main vehicle, once the latter is halted. This enables the relation between the curvature of the track, the laser reference chord data and the GPS co-ordinates to be established. On at least one calibrated reference point (at a distance of 4km for example), a GPS reference receiver is located and equipped with a notebook for data recording. Both systems (reference receiver and rover) are linked to each other via radio.

While the satellite trolley is moving forward, the GPS receiver data are

received and stored on the notebook. The system operates on-line in real time, but off-line processing of the measured data is recommended, as the EM-SAT continues to work with undiminished quality even if the radio connection is interrupted. Not until the end of a measuring period are all the collected data put together to calculate the absolute track geometry co-ordinates and track correction values.

**Use of the combined EM-SAT – GPS system**

Simultaneous measuring of the actual track with laser reference chords and GPS makes it possible to store the laser reference chord (working in a local co-ordinate system) in the absolute WGS84 system, and thus to transform the high accuracy relative laser reference chord data into absolute co-ordinates (WGS84). Almost any measured GPS co-ordinate can in principle be used as a fixed point (Fig. 7). Without a significant amount of extra work or cost, the following benefits can be obtained:

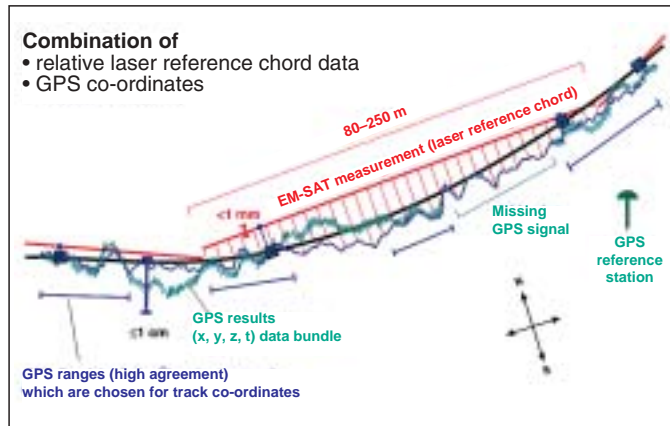


Fig. 7: Combination of laser reference chord measuring and GPS co-ordinate measuring

- ▷ Repeated measuring periods of the system will allow conclusions to be drawn on the availability and accuracy of GPS measurements. This will allow the accuracy of GPS measurements to be charted and help to determine where traditional fixed points can be dispensed with. The comparison of the high precision laser reference chord data with the GPS measuring data will allow conclusions to be drawn on the quality of the GPS reception (multipath, etc.).
- ▷ On unmarked track, track co-ordinates with a very high internal accuracy and an accuracy in the order of 1 cm at the chord end points are obtained. These provide an excellent basis for the layout of a line or for line improvements by the surveying engineer. Using the combined EM-SAT-GPS system brings enormous potential savings compared to geodetic measuring methods.
- ▷ Once the target position of the track is defined by its WGS84 co-ordinates, the combined system is able to measure

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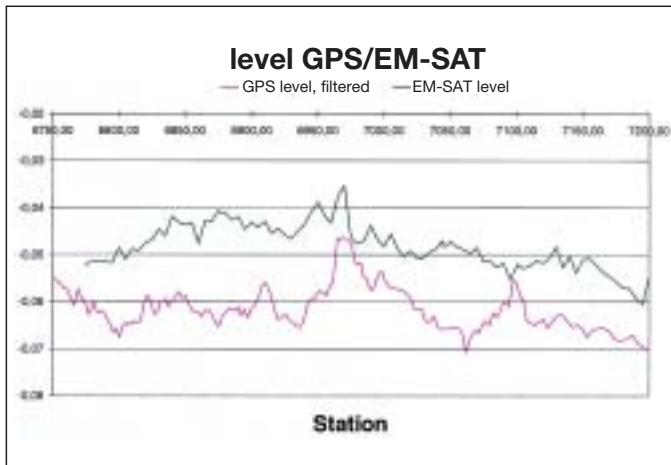


Fig. 8 : Comparison between EM-SAT laser reference chord measuring and GPS measuring for the longitudinal level

the EM-SAT with GPS will result in a system that does not only deliver correction data for maintenance machines, but is also able to supply absolute coordinates of the track geometry to the surveying engineer without significant extra costs.

This system will not only be of interest to countries with marked tracks, but especially for the railway administrations that are seeking a new way of surveying the track.

The optional addition to the system of a non-contract laser-assisted ballast profile

the deviation of the track from the target values at any time. Any point on the track, where GPS data is obtained, may be used as a fixed point. There would no longer be a need for defined fixed points – these could be freely chosen. Fig. 8 shows the result of a comparison between a laser reference chord measurement and a GPS measurement.

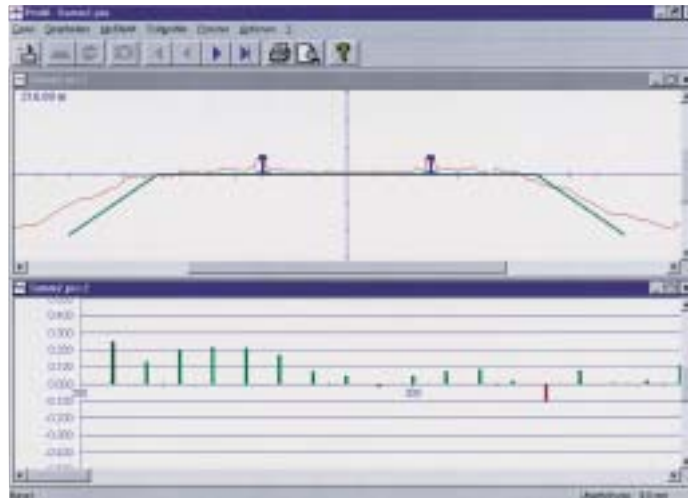


Fig. 9: Monitor display of the ballast profile system

## Possible extension of the EM-SAT to include a ballast profile measuring system

When planning the possible lifts, based on the measured lifting correction values, the actual ballast profile on site is an important parameter. To perform the lifts, sufficient ballast must be available for tamping. The non-contact laser-assisted ballast profile measuring device is a system that is able to record the actual ballast profile continuously. In combination with the EM-SAT, the permanent way district obtains a tool that enables a further reduction of effort (elimination of line inspection, ballast management) and savings in costs.

Every 2 m a measured profile is recorded, while a comparison between the actual ballast profile and the target ballast profile is used to calculate either the excess or the lack of ballast, which is represented as a bar chart. The profiles and the differences in volume can be displayed and processed further on a PC in an office environment. Fig. 9 shows the work screen, where the target ballast profile is displayed in green and the red line represents the actual ballast profile. The measured area can be enlarged or reduced at will, depending on whether the side path or the adjacent track is shown. Target

profiles can be input, changed or expanded via pairs of co-ordinates.

## Summary

EM-SAT and the fixed point measuring device represent two well proven systems that allow automated and mechanised track measuring in an efficient, labour and cost saving manner.

Mechanised measuring using EM-SAT allows cost savings of DM 6 per measured metre in comparison to the traditional manual and optical method. In addition, the output of the tamer is increased by 50 % on plain track, as it is no longer necessary to bring forward the laser unit and the start and end points for tamping are predetermined.

According to a profitability evaluation conducted by DB Netz AG, the new system "EM-SAT with GPS" will allow further significant cost savings.

In the coming years, the combination of

measuring system enables the planning engineer to make decisions in terms of possible lifts (ballast requirements) without carrying out a line inspection.

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