# THE RAPID TUNNEL REFERENCE SURVEYOR FOR A FUTURE LINEAR COLLIDER

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**Abstract**

For future linear colliders, accuracy demandments for the alignment of the components below 1mm per 600m length require new, refraction-free measurement systems. Combined with economic requirements, e.g. cheapness of the system and little downtime of the accelerator, this leads to the idea of a measurement train called "Rapid Tunnel Reference Surveyor". This system, based on the principle of multipoint alignment, eliminates the influence of refraction on the straightness measurement and works without user interaction. Two different refraction-free realisations of this concept are developed: **GeLiS** uses a stretched wire as straightness reference and a new HLS with in-situ calibration as height reference. **LiCAS** uses a laser beam in vacuum as straightness and length reference in all three dimensions.

## 1. INTRODUCTION

Future linear accelerators require new survey techniques to achieve the necessary alignment precision. The standard deviation of every component is postulated to be $\sigma_{l,h}$ = 0.2mm in lateral and height over the maximum betatron wavelength (e.g. 600m for TESLA, other accelerators may have even longer wavelengthes). These demands can not be fulfilled with common, open-air geodetic methods, mainly because of refraction in the tunnel. Therefore the RTRS (Rapid Tunnel Reference Surveyor), an approximately 25m long measurement train, performing overlapping multipoint alignment on a regular tunnel reference network, is being developed. Two refraction-free realisations of this concept are being under construction at the moment:

**GeLiS** measures the horizontal co-ordinates using multipoint alignment with stretched wires as straightness reference. In areas of the tunnel where the accelerator is following the earth curvature GeLiS measures the vertical co-ordinate using a new hydrostatic levelling system (HLS). A brief report about the status of GeLiS is given in this paper.

**LiCAS** is based on laser straightness monitors (LSM) combined with frequency scanning interferometry (FSI) in an evacuated system. LiCAS measures both co-ordinates with respect to its LSM-beam and thus is suitable for geometrically straight tunnel sections. For details on the working principle of LiCAS, see [1] and [5].

Both measurement systems will be placed on a train, which could do the reference survey autonomous or semi-autonomous. The coordinates are transferred from the reference network at the tunnel wall to the components of the machine using a Lasertracker or Tacheometer. This instrument could be mounted on the train or on a separate carriage.

## 2. CONCEPT

A basic network of reference points fixed to the wall in an equidistance of approximately 5m is installed in the tunnel. The alignment of the accelerator is split up in two major steps:

1. The reference points will be determined by an automated system (RTRS) in 3D space.

2. The coordinates are transferred to the machine components with a tacheometer or a lasertracker. This step is geodetic standard work and is not described in this paper. It is planned to integrate this second step into the RTRS.

### 2.1. Multipoint Alignment

With the technique of multipoint alignment [9] the effects of refraction can be eliminated or reduced if a mechanical structure or a laser beam in vacuum is used as straightness reference. Multipoint alignment in a simplified 2D context means that the lateral distances $s_{i-1}$, $s_i$ and $s_{i+1}$ (see Figure 1) between the straightness reference and several reference points are measured. Together with the distances $s_{i-1,i}$ and $s_{i,i+1}$ the angle β and the distances d can be calculated. This is done sequentially for every reference point in the tunnel (see Figure 1). A traverse then is used to estimate the coordinates of the reference points. LiCAS extends this concept to a 3D-measurement.

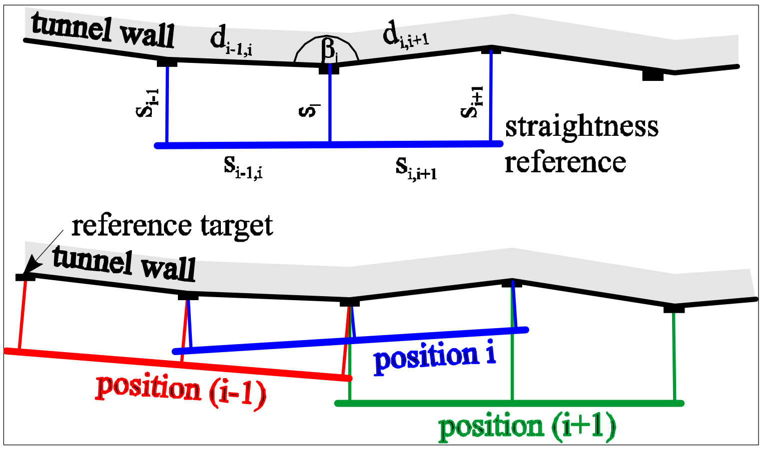


**Figure 1: concept of geodetic reference survey (simplified 2D)**

### 2.2. Rapid Tunel Reference Surveyor (RTRS)

A train with six measurement cars (blue, see Figure 2) will overdetermine the multipoint alignment problem and provide enough redundancy to obtain the desired accuracy and reliability. For electronics and drives additional service cars (grey, see Figure 2) are needed. This train can act autonomous and moves through the tunnel without user interaction.

It is planned to put a lasertracker on top of a measuring car to do some survey work on the components, while the train is measuring the reference network. In this special case an operator must move through the tunnel with the train and put the retro-targets onto the components. A fixed installation of standard targets fails due to the limited apex angle.

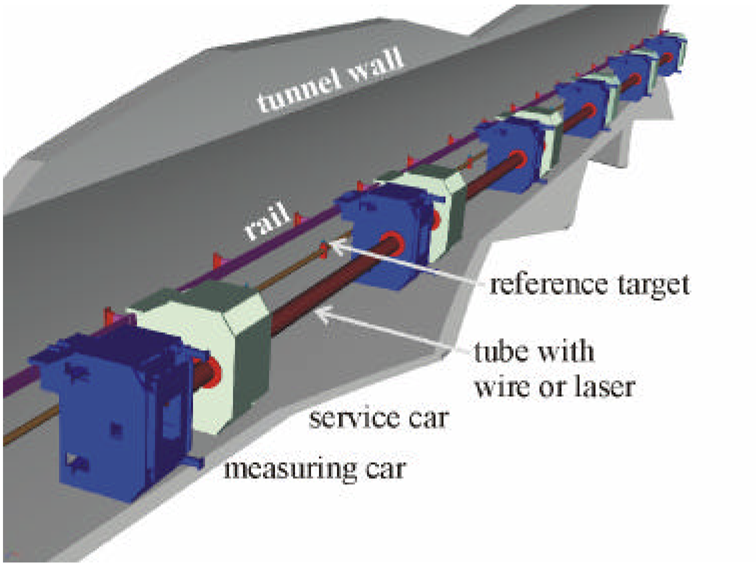


**Figure 2: measuring train on the tunnel wall**

## 3. THE GELIS METROLOGY SYSTEM

A stretched wire is used as a straightness reference in the GeLiS-train. This wire runs through the whole train in a closed tube to prevent influences from external forces. It is fixed at the front and rear of the train only and thus provides a straight line, when projected onto the horizontal plane.

In every single car the distance between the reference target (A, see Figure 3) and the wire (C) is measured with two optical 3D-sensors (B, D) and two incremental length gauges (E, F). The cameras (H) are used for rough positioning. (G) is the measurement vessel of the HLS. Because the measuring range of the 3D-Sensors is only a few millimetres the sensors have to be mounted on movable stages so that they can compensate for the tunnel tolerance of several centimetres. The tilt of the inner block is measured by a biaxial tilt sensor (K) and adjusted to zero with the stages. The distance between the wire (C) and the target (A) is measured with an accuracy of 3µm.

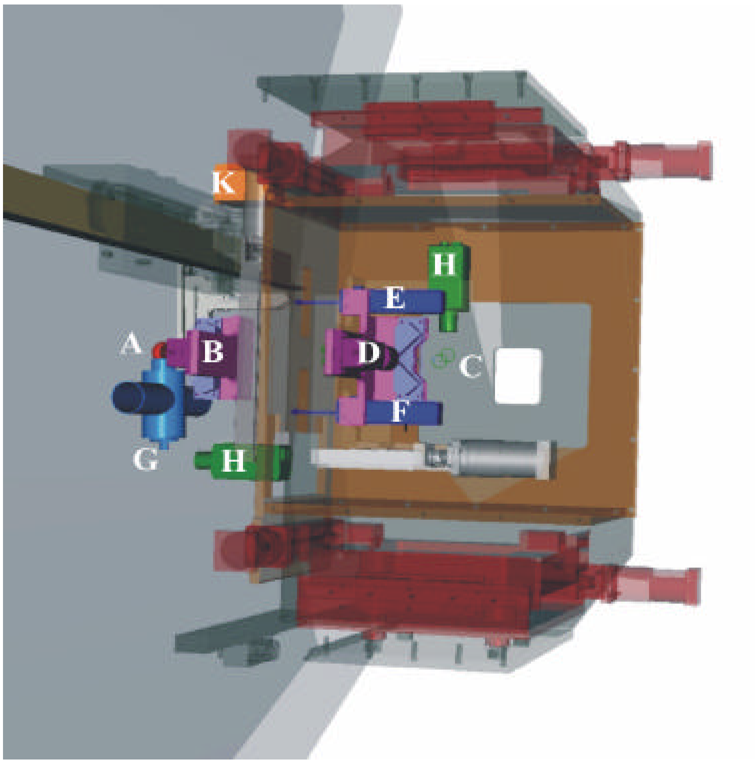


**Figure 3: A GeLiS car in the tunnel**

## 3.1. Optical 3D-sensor

For the contactless distance determination an optical sensor consisting of a digital camera and a split image prism is used (see Figure 5). The distance Δy between the two image parts on the CCD gives - together with some calibration constants - the distance Δx (see Figure 5 and Figure 4).

The main advantage compared to a two-camera stereo solution is that there is no special stability requirement for the relative position of the cameras. There is only the easier stability requirement of the prism.


**Figure 4: view from the outer 3D-sensor**

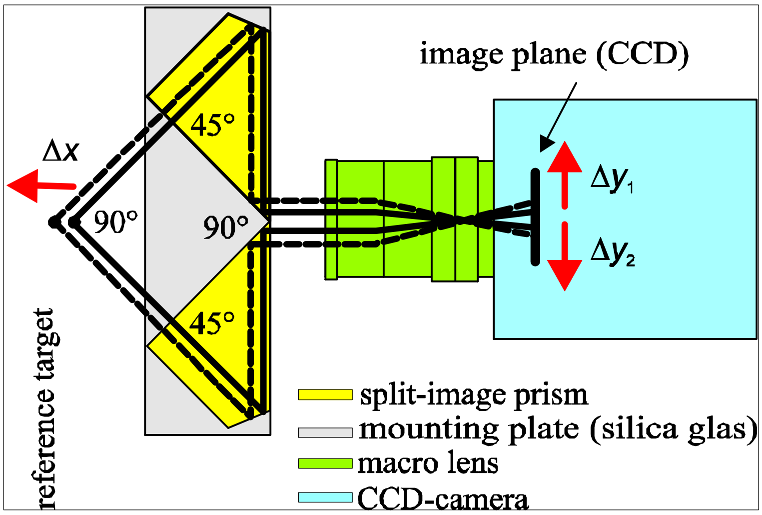


**Figure 5: optical 3D-sensor**

### 3.2. GeLiS Prototype

To date a one car GeLiS Prototype has been constructed (see Figure 6). Tests of functionality and repeatability are in progress. Software for the sensors and the motion stages is being improved. A mathematical model for the least squares adjustment of all measured data is also being developed. The continuation of the GeLiS version of the RTRS project is doubtful due to serious cuts in its budget.

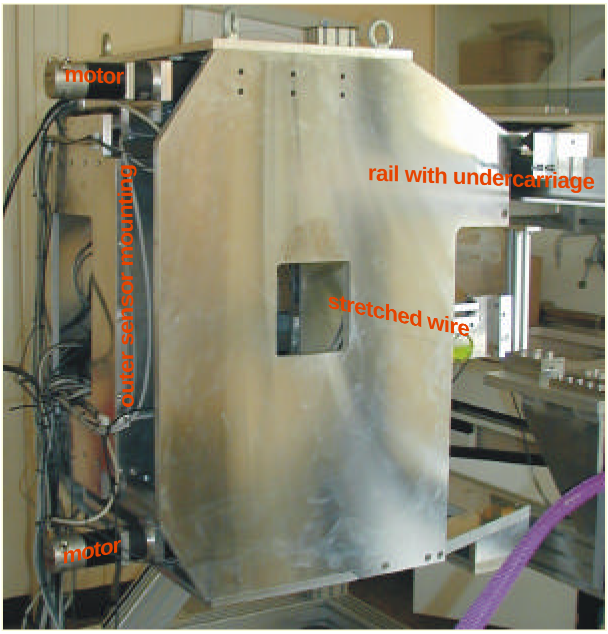


**Figure 6: GeLiS Prototype, view from the tunnel side**

## 4. HYDROSTATIC LEVELLING SYSTEM (HLS)

Since the accelerator could follow the curvature of the earth and the wire has limitations as height reference because of the sag, a drift-free HLS was developed.

### 4.1. In-situ calibration for HLS

To eliminate the effect of temperature differences between the measurement vessels, a system with a free surface is used [7], [8]. No external forces provided, this surface is an equipotential expanse. The surface is then sampled using an ultrasonic system, the distances $R_1$, $R_2$ and OF (see Figure 7) are measured simultaneously. Due to the calibrated distances $D_1$ and $D_2$ a calibrated estimation of $H_P$ is done by

$$H_P = H_W + D_2 - D_1 \frac{OF - R_1}{R_2 - R_1} \tag{1}$$

with $H_W$ beeing the heigth of the water surface.

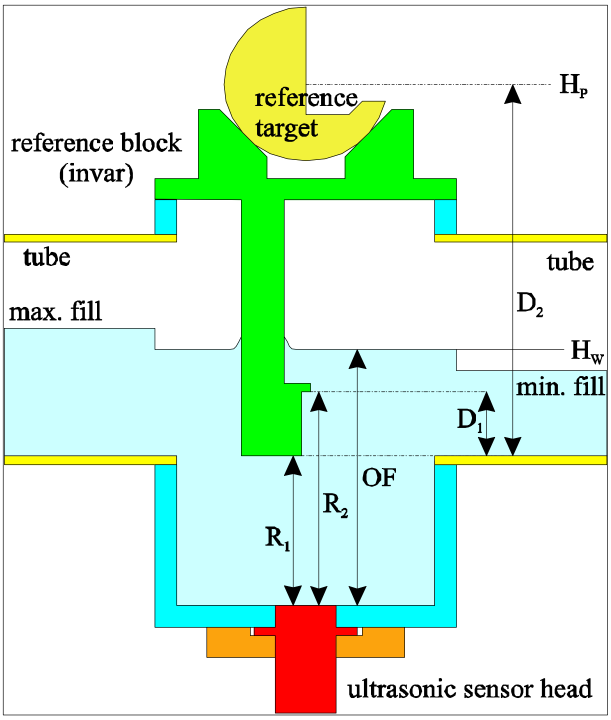


**Figure 7: HLS measurement vessel**

### 4.2. Improving the accuracy of the USM25

As ultrasonic measurement device an USM25 [3] has been used so far. This device is originally used for non-destructive material testing and thus has some limitations concering precise distance measurements. It is impossible, for example, to get the signal propagation delay directly, it is always reduced to a distance with the given sound velocity. This distance has a resolution of 10µm in the measuring range of up to 10cm, while the accuracy of the USM25 is in fact better [7], [8]. With using Formula (1), the scale and the additive constant both drop out of the result. It is therefore possible to use a high sound velocity (scale) and a high probe delay line (additive constant) to spread the measured signal over the whole range of 0 to 10cm. With this it is possible to improve the accuracy of the USM25 to ~3µm.

### 4.3. Improving the accuracy with the new CL400

With a new ultrasonic measurement device CL400 [4] the accuracy can be improved to less than 1µm. First results of a calibration of this device against a Heidenhain MT60 incremental length gauge are shown in Figure 8. With the same method described in 4.2 it should be possible to improve the accuracy to less than 1µm. That means that a standard deviation for the height difference between two measurement pods of $\sigma_{\Delta H} < 5\mu m$ can be achieved easily [7], [8].

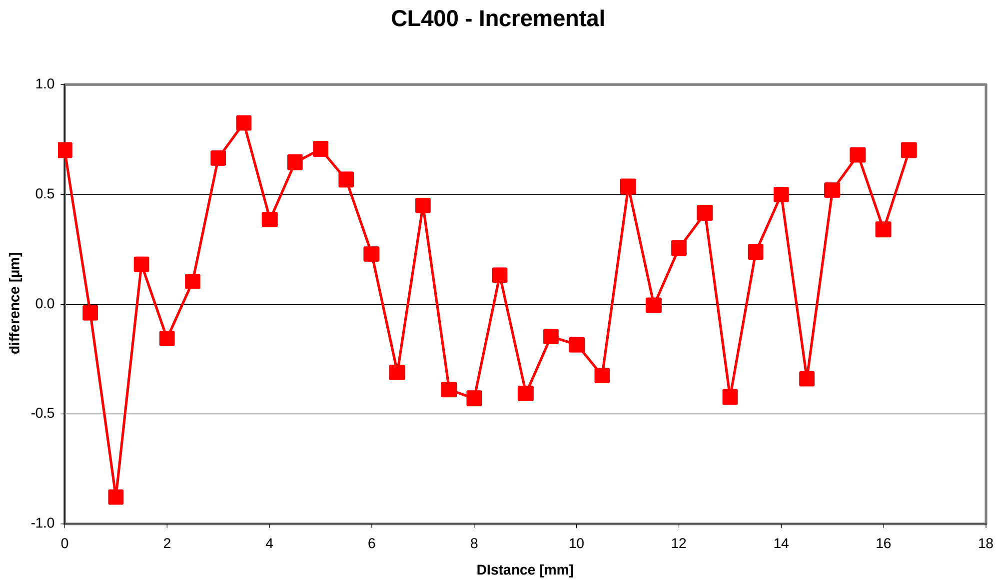


**Figure 8: calibration results of CL400**

## 5. SUMMARY

The concept of a multipoint alignment system on an autonomous measurement train is a possible solution for the measurement of a reference network for future linear accelerators. Two different realisations of this concept are developed. While the GeLiS part of this project has a one car prototype ready, it is discontinued due to serious budget cuttings. The LiCAS part of this project is not affected by this and a three car prototype of the LiCAS system will be ready in 2005. The development of a drift-free HLS, originally part of the GeLiS project, is continued. Improvements in accuracy have been shown.

## References

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