

# HIGH PRECISION SURVEY AND ALIGNMENT OF LARGE LINEAR ACCELERATORS

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## Abstract

Future linear accelerators require new survey techniques to achieve the necessary alignment precision. For TESLA, the demanded accuracy for the alignment of the components is 0.5mm horizontal and 0.2mm vertical, both on each 600m section. Other proposed linear colliders require similar accuracies. 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), a 25m long measurement train performing overlapping multipoint alignment on a regular tunnel reference network is being developed. Two refraction-free realizations of this concept are being developed 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).

**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. Both measurement systems will be placed on a train, which could do the reference survey autonomous or semi-autonomous.

## GEODETIC TASKS

A very high accuracy is demanded for the alignment of all accelerator components to run the linear collider successfully. The standard deviation of every component is postulated to be  $\sigma_{1,h} = 0.2\text{mm}$  in lateral and height over the maximum betatron wavelength (e.g. 600m). Because of the influence of refraction, this requirement can not be achieved with any open-air optical survey.

## 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 (Rapid Tunnel Reference Surveyor, RTRS) in 3D space. The RTRS is described here.
- 2) The coordinates are transferred to the machine components with a tachometer. This step is geodetic standard work and is not described in this paper. It is planned to integrate this second step into the RTRS.

## Multipoint Alignment

With the technique of multipoint alignment 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 Fig. 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  $\beta$  and the distances  $d$  can be calculated. This is done sequentially for every reference point in the tunnel (see Fig. 1). A traverse then is used to estimate the coordinates of the reference points. LiCAS extends this concept to a 3D-measurement

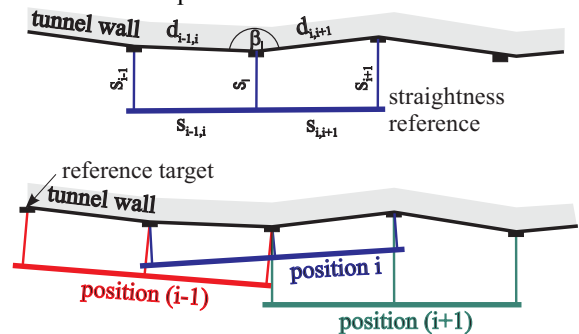


Figure 1: concept of geodetic reference survey, simplified 2D

## Rapid Tunnel Reference Surveyor, RTRS

A train with six measurement cars (blue, see Fig. 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) are needed. This train can act autonomous and moves through the tunnel without user interaction.

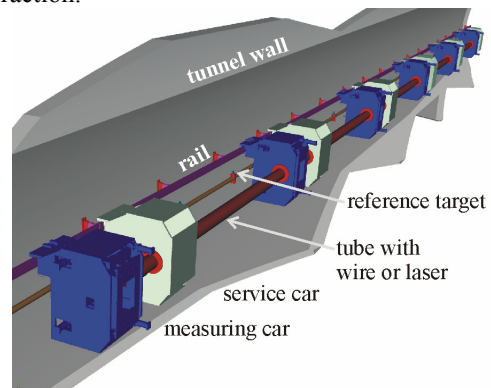


Figure 2: measuring train on the tunnel wall

## THE GELIS<sup>®</sup> 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 Fig. 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 centimetre. 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.

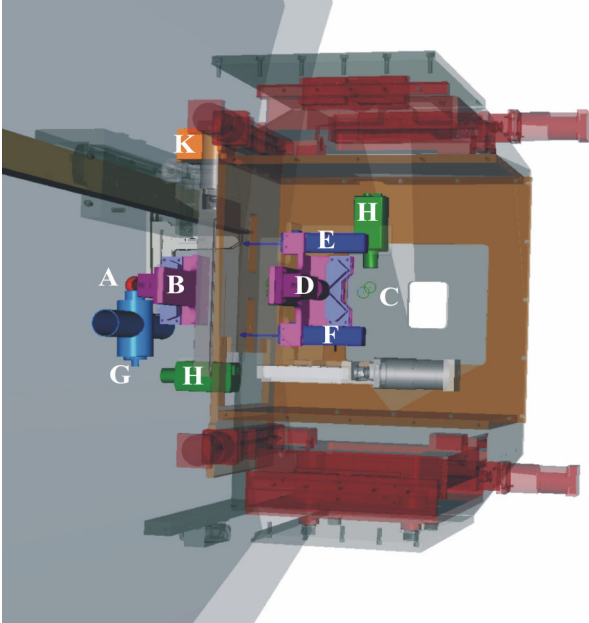


Figure 3: A GeLiS car in the tunnel

### Optical 3D-sensor

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

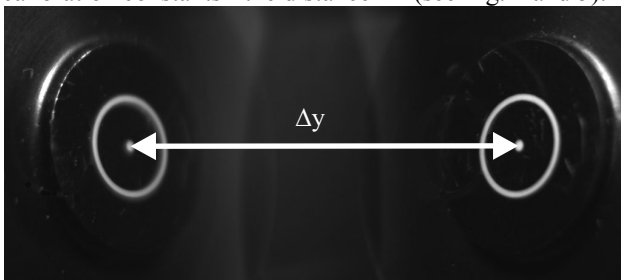


Figure 4: view from the outer 3D-sensor

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.

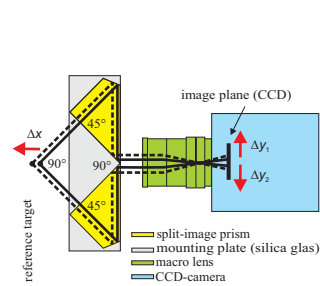


Figure 5: Optical 3D-sensor

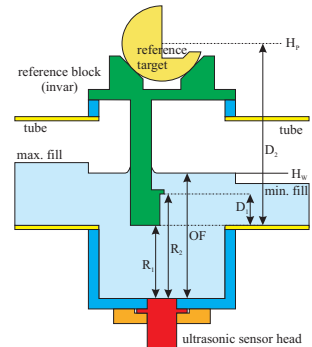


Figure 6: Ultrasonic measurement pot

### 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. To eliminate the effect of temperature differences between the measurement vessels, a system with a free surface is used. 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 Fig. 6) are measured simultaneously. Due to the calibrated distances  $D_1$  and  $D_2$  a calibrated estimation of  $H_p$  is possible.

### GeLiS Prototype

To date a one car GeLiS Prototype has been constructed (see Fig. 7). 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.

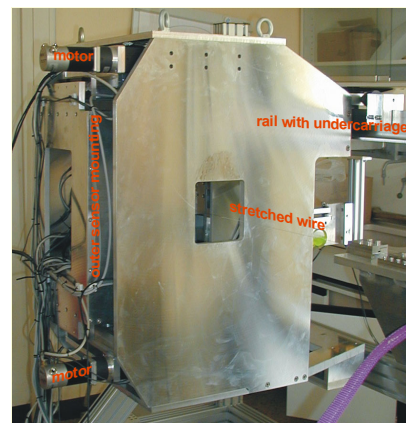


Figure 7: Prototype, view from the tunnel side

<sup>®</sup>GeLiS: GEodetic measurement train for LInear accelerators and linear Synchrotron radiation sources

## The LiCAS\* Metrology System

The LiCAS project aims to construct a metrology system for the RTRS with the following properties:

- Capable of measuring a tunnel reference network independent of the geoid by use of a geometrical straightness and distance definition making it suitable for geometrically straight or inclined tunnels.
- Redundant and rapid measurement procedure avoiding the use of precision movers in the measurement process.
- High intrinsic sensitivity and maximum reconstruction power, enabling in-situ calibration procedures to minimise systematic errors

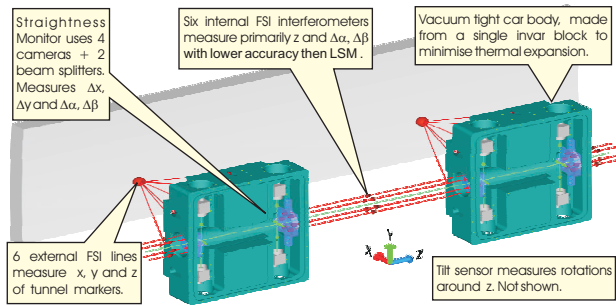


Figure 8: Two LiCAS cars without mechanical framework and vacuum system.  $\Delta\alpha$ ,  $\Delta\beta$  refer to rotations around x and y.

The LiCAS cars measure their relative position and orientation using a laser straightness monitor (LSM) and an internal FSI† system. The LSM beam is launched by the first car and accurately retro-reflected by a corner cube reflector in the last car. Each car measures the LSM beam with 4 CCD cameras. This redundantly determines transverse offsets and rotations around x and y. Six internal FSI distance measurements primarily determine the relative offset in z but are also sensitive to rotations around x and y. Rotations around z are measured by a tilt sensor (not shown). All intra-car measurements are performed in vacuum to avoid refraction problems. The position of each reference marker is measured by its car with 6 external FSI lines.

### Performance Simulations

To study the expected errors and correlations of reference marker position reconstruction, a geometrical simulation of the LiCAS-RTRS, using the SIMULGEO [1] software package, was performed. The long-distance operation of the train was simulated by a set of identical trains displaced by one marker separation. SIMULGEO's

\* LiCAS = Linear Collider Alignment and Survey,

† FSI = Frequency Scanning Interferometry, a method for accurate distance measurement

approach of manipulating very large matrices‡ is very time and memory consuming. Therefore a simplified analytical formula derived from a random walk model with direction correlation between steps was used to extrapolate the SIMULGEO predictions over long distances. The error on the  $n$ 'th reference marker is then

given by: 
$$\sigma_{n,x} = \sqrt{l^2 \sigma_{\alpha_x}^2 \frac{n(n+1)(2n+1)}{6} + \sigma_x^2 n}$$
, where  $l$  is the distance between cars,  $\sigma_{\alpha_x}$  is the angular and  $\sigma_x$  the transverse offset error between consecutive train stops.

These errors were obtained by fits to the SIMULGEO simulations. A large series of random walk trajectories was generated whose RMS-residua with respect to a straight line give the survey accuracy. Figure 9 demonstrates that a vertical precision of  $O(200 \mu\text{m})$  over 600 m is feasible.

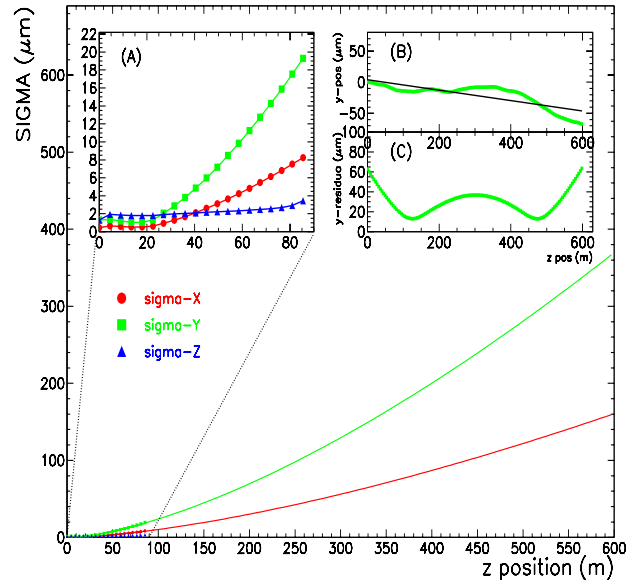


Figure 9: LiCAS train simulation: (A) Simulgeo simulation; (Main) random walk extrapolation to 600m; (B) Example of a random walk trajectory with a straight line fit. (C) RMS residua distribution of many random walk trajectories.

## REFERENCES

- [1] L. Brunel, "SIMULGEO: Simulation and reconstruction software for optogeometrical systems", CERN CMS Note 1998/079.

‡ With sizes similar to the number of measurements; eg.  $O(2.000)$  for an 80 meter tunnel segment.