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SURVEY WORKS FOR L3 EXPERIMENT

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1. Introduction

The importance of the role of the geodesists in the alignment of particle accelerators is generally accepted; on the other hand, their role in the alignment of the physics experiments themselves is less well known. This paper will give an overview of what was done on the alignment of the L3 experiment on the low-electron positron (LEP) machine at CERN and draw certain conclusions for the alignment of the next generation of collider physics experiments.

1.1 Surface Geodetic Network

The base of all geodetic works on a particle accelerator is the site surface geodetic network. This net of points measured to the highest precision possible guarantees the parameters of the new machine and its relationship to any preexisting components of the accelerator chain. The positioning of the machine and experiment is carried out concurrently; the common relationship to the surface geodetic network assures the alignment between the accelerator and the experiment.

1.1.1 The LEP Geodetic Network

The LEP surface geodetic network consists of five (5) pillars covering the spatial extent of the LEP machine and five (5) pillars known in the CERN reference system, these latter points providing the link to existing machines, such as the Super Proton Synchrotron (SPS). The measurements were carried out between all pillars using a two-color laser distance measuring device (precision 10^{-7}). An accelerator is a plane in geometrical space. Survey/geodetic measurements are in general made with reference to the local vertical (line described by a plumb bob). A mass model was developed and checked by astral observations to correct for the divergence of the local vertical produced by the proximity of the Jura mountains. The coordinates of the surface network were transmitted to pillars in the LEP tunnel itself by the eight access pits.

1.2 Alignment of the LEP Machine

The alignment of the accelerator itself involves an initial positioning of the components at their theoretical position to avoid distortion of the design parameters of the machine and subsequent smoothing to guarantee the relative alignment of adjacent magnetic elements to within a tenth of a millimeter.

1.3 Survey Alignment of a Physics Experiment

The responsibility of survey alignment for physics experiments at CERN is twofold.

- Responsibility to Experimental Collaboration—To provide technical aid to the collaboration (verification of theoretical parameters) and to provide coordinates for the external survey database (approximate values for alignment by track fitting).

- Responsibility to Experimental Collaboration and Machine—To assure the correct alignment of common elements of the accelerator, the most important being the experimental magnet.

- "Russian Doll Metrology"—The L3 detector differs from the other LEP experiments because it is built directly on the beam line and because of its structure. The structure of the experiments ALEPH, DELPHI and OPAL can be compared to that of a set of Russian dolls. In such a case, the installation of a detector hides another. The technique developed for the alignment of large nondeformable composite objects of this type was christened "Russian doll metrology." It is the establishment of a cascade of spatial relationships between parts of a modular object at various measurement epoches, which allow the subsequent mathematical recreation of the complete object once it is fully assembled. Four (4) levels of relationships can be distinguished.

  - Internal Geometry: The definition of the relationship between the physics reference and the survey reference on the detector.

  - Detector Geometry: The spatial description of a modular object using the survey reference points.

  - Relative Geometry: The establishment of a cascade of spatial relationships between adjacent detectors.

- Definitive Geometry: The position of all detectors on beam-line deduced from above relationships.

Russian doll metrology is often the only means available to supply a complete spatial description of an experiment on the beam-line. It requires however a very important planning effort in particular for the definition of the timing of intervention and to assure that the common points necessary for the transfer of relationships are always visible. From the point of view of installation, it is advantageous because most survey work is done before installation of the experiment on the beam-line. However objects are assumed to have an unchanged spatial relationship through time which is often not the case. The truth of this assumption can only be checked by the alignment systems of the detectors themselves.

2. Brief Overview of Survey Operations on the L3 Experiment

2.1 Survey Preparation Works

It is essential to incorporate survey from the establishment of the collaboration and to include it in the working groups. E. Menant started to follow the LEP experiments from the middle of 1983. He was named as survey linkman in the technical proposal of L3, dated May 1983. This early involvement had the following aims.

- Preliminary Exchanges of Information: It is essential to explain what survey can do, cannot do and has done. A preliminary appraisal of the needs of a detector can be conducted by means of a simple questionnaire. Survey technical advice may be required vis-a-vis survey during manufacture of the detector or survey requirements in calls for tender.

- Definition of Survey Reference Marks: It is rare that survey measurements can be made directly on the physics reference for a detector, thus survey fiducial marks have to be created at a known position with respect to the physics reference system. It is better to establish this essential relationship during the manufacturing process as the physics fiducial marks are more readily available. The type and position of the survey reference is thus chosen before the survey procedure is finalized. This is why precise holes which allow the interchangeability of targets were requested for most LEP detectors. The procedure for the establishment of the relationship physics survey reference must be known to the surveyor.

- Survey Linkman for Each Detector Group: It is essential to have one representative for each detector who is charged with the survey dialogue. The

role of this person in the detector group must be clear and the person must be informed and reasonably available.

- Precisions: Before a discussion of survey procedures can start, it is essential to have an idea of the precision required for survey measurements on a given detector and to understand the reasons for this request.

- Definition of Survey Procedure: Theoretical studies and simulations play an essential part in the definition of survey operations because of the complexity of installation procedures and the limited optical access to survey fiducial marks. Certain problems may require development of instrumentation and tests. The cavern geodetic network evolves in function of the definition of survey procedures.

2.2 Estimate of Survey Workload for L3

The field survey work on the L3 experiment involved over 300 interventions, the majority in the two years preceding the start up of the LEP (see Table 1).

Table 1. Survey Work by Zone

Zone	No. of Survey Reports Distributed	Period
TEST BEAM	40	
		4/83 to 7/89
SXL2		
Support tube and		
coil assembly	63	
trial assembly	37	1/87 to 12/87
		1/88 to 11/88
UX25		
infrastructure	50	
magnet assembly	58	1/87 to 11/88
detector installation	44	9/87 to 8/88
		11/88 to 7/89
LABORATORY/ WORKSHOP	23	
		4/87 to 6/89
OUTSIDE CERN	5	
		11/86 to 10/87
Total	320	

The number of meetings necessary for the preparation and the follow-up of these interventions is difficult to evaluate. One meeting a week for the period April 1983 to July 1989 for at least one member of the CERN survey group (survey engineer) is a conservative estimate.

The post start-up workload is obviously less heavy, but preparation for phase II and maintenance measurements for the database continue.

2.3 Subdivision of Survey Works

The survey operations carried out on the L3 experiment (Table 2) can be subdivided as follows.

- Preparation of Experimental Zone: Materialization of coordinated points, control parameters of cavern, alignment bridge cranes; for example, the verification of the position of the counting rooms in PX25.

- Dimensional Control: The verification of certain parameters of objects in laboratory, workshop or factory, often as part of an acceptance procedure; such operations were carried out on the magnet crown and support tube prior to transport to CERN.

- Geometrical Calibration: The spatial description of an object by survey measurements; an example of this was the measurement of the relationship between crystals and survey reference marks for the BGO barrel.

- Prealignment: Measurements to optimize alignment before installation in data-taking position; can be cited the pointing of muon octant center lines towards axis of torque tube.

- Alignment: Measurements to optimize alignment during installation in data-taking position; an illustration of this was the on-line guiding of the 28 coil packets during installation.

- Metrology for Database: Measurement of the object in its data-taking position to provide spatial coordinates for the external survey database and maintenance of this data bank; in the case of L3, prevision of 315 reference points on 52 detector units to a submillimetric precision.

Table 2. Subdivision of Survey Works as Performed on L3 Detectors

Detector	Dimensional Control	Geometrical Calibration	Pre-alignment	Alignment	Metrology
Support tube	X				
and magnet			X	X	
Muon filter					X
Hadron barrel		X	X		X
BGO barrel		X	X		X
TEC					X
Hadron endcaps			X	X	X
Luminosity monitor		X			X
Muon barrel		X	X	X	X

2.4 Some Implications of Survey for Experiment Installation

2.4.1 Detector Services

In general for L3, the survey got on with the mechanical installation but not the services. Nearly 20% of the survey reference marks foreseen for the external survey database were not measured because of obstruction of the optical path by the services of the detector. This suggests that a greater contact with people responsible for the design of the detector services is necessary. However this effort is required very late in the installation, when surveyors are very much occupied by the realization of the installation alignment.

2.4.2 Services

A part of the survey work which was largely ignored during the preparation was the control of installations made in the cavern by outside firms. The work was performed to check if contractual tolerances were respected. The improvisation of such measurements was not always easy.

2.4.3 Geodetic Cavern Network

An indispensable element of the survey alignment of a physics experiment is the cavern geodetic network, a series of stable points at strategic locations, whose spatial coordinates are known with respect to the theoretical beam to a few tenths of a millimeter and which acts as a large calibration bench. It is the homogeneity, precision and continuity through time of this knowledge which determines the survey measurement accuracy between spatially separated detectors. The network evolves following the advancement of the installation, this must be taken into account for zone demarcation. The materialization of the net (survey brackets, pillars, etc.) require space, stability and optical intervisibility. The definition of essential optical paths is required, but any restriction to the optical accessibility of a point reduces the possibility to meet unforeseen survey applications.

2.4.4 Survey Working Conditions

The use of the tripod gives much of the versatility of survey alignment, however it is very susceptible to disturbance. An exclusive use of an area during measurement is not always possible, for this reason most precise survey work in the L3 support tube was done outside normal working hours. It should be noted that the use of rails and the prealignment of detectors reduces the planning problem and sometimes takes survey off the critical path of installation.

2.4.5 Liaison

For L3 the distribution of role and responsibility was not as clear as it could have been in the detector groups or for that matter in the survey. Time was lost in the search for the correct person and the correct information.

3. Survey Alignment and Mechanical Alignment

3.1 Survey Alignment on Physics Experiments at CERN

The requirements for alignment of physics experiments at CERN requires the use of a variety of techniques, not always associated with those of surveyors.

3.1.1 Survey Techniques

The use of surveying techniques gives the versatility, transportability and adaptability of application, however the level of precision obliges the use of high-quality equipment; for example, electronic theodolite (angular resolution 10^{-6} radians), geodetic level (resolution

10 microns), electro-optical distance meters (resolution 200 microns) and an important computing effort. The latter is firstly to facilitate and increase the speed of measurement treatment, and secondly for the rigorous block adjustment of divers redundant measurements.

3.1.2 Industrial Triangulation

In recent years the need of industry for precise, rapid, no-contact measurement on large objects has produced a technique based on theodolite intersection. This method, the description of an object by coordination of points, intersected from two or more electronic theodolites in a common reference system, with on-line data capture, treatment and organization by portable computer has been largely adopted and adapted for the alignment of physics experiments at CERN.

3.1.3 Mechanical Alignment

The precision realized for the alignment of particle accelerators at CERN owes much to the use of mechanical alignment, i.e., nylon offset device, distinvar. These instruments are available for the alignment of the experiments. Other techniques and instruments adapted or developed include the use of a theodolite/level as an alignment telescope, digital calipers, autocollimation, autoreflection, etc.

3.2 Comparison of Mechanical Alignment and Industrial Triangulation

	Industrial Triangulation	Mechanical Alignment
Typical Instrumentation	Two or more theodolites with on-line computer	Calipers, tilt meters, dial micrometer, alignment, telescope, etc.
Results	Coordinates in a local reference system, related to vertical	Parameters, such as straightness, length, tilt, perpendicular offsets
Further Treatment	On-line fits to theoretical models, inclusion redundant information	A priori no redundant information, independent check, if possible
Measurement	Indirect, coordinates do not always give characteristics required	Direct
Precision	Dependent on geometry of intersection, at best several hundreds of microns on object up to 30 m	Tens of microns, but problems with increasing scale for gauges, calipers, etc. (handling, stability, etc.)
Access	Noncontact, optical access from eccentric stations	Often physical access and/or unobstructed plane or line close to object
Monitoring	In development	Well-established
New Trends	Amelioration of soft, work on remote measures	Mechanical and electronic development (LAA)

Survey and mechanical alignment should be seen as two complementary techniques requiring a careful adaptation of method to application. Cross-checking between the two is always desirable, it increases confidence and avoids misunderstanding of mistakes.

Survey seems particularly appropriate for the noncontact spatial description of large objects, where treatment and redundancy gives an idea of the quality of the measurement. The setting of zeroes with reference to a nonmaterialized coordinate system is also well adapted to the survey technique.

The on-line guiding by survey (use of theodolite as alignment telescope) should be avoided, this adaptation of instrument is prone to errors of interpretation. On the other hand, mechanical alignment is very suitable for this task, it is direct, trusted by engineers and if the reference is well chosen leaves little room for error. A verification by survey means is always useful. For example in L3, a prealignment of the hadron calorimeter guide rollers and the guide rail in the support tube should have centered the inner ring of this detector on the beam. However a survey measurement after installation revealed that this was not the case, the weight of the detector had increased the distance between the rails, thus moving the reference for the mechanical alignment.

4. Next Generation Collider Physics Experiments

All analyses in this section are based on the document, "Experimental Area for a High Energy Detector," dated 31 October 1989.

4.1 Cavern Geodetic Network

The design of the cavern geodetic network is a two-stage process.

- Primary Net: The design of the primary net is a priori to provide a link to the machine reference system and to provide a basic coverage of the cavern. In the final L3 cavern network, there were 10 points of this type. These points should be at the same height as the survey reference plane for the machine or failing that above the maximum height of the accelerator magnets. The plan position of such points with critical optical paths is shown in Figure 1.

- Secondary Net: Points in the secondary net are positioned for specific measurements on the detectors. The design will thus evolve following the definition of survey procedures and the stage of installation. In the final L3 cavern network, there were over 30 points of this type. The majority were positioned to allow the observation of the interaction point (IP) survey references on the muon octants, which had a very limited optical access (15 degrees). In the case of L3, the backwall was a suitable support for these

points. However in the report cited above, the walls of the experimental cavern perpendicular to the beam are too far from the IP for precise measurement (5^{cc} at 50 meters equals a vector of 0.4 mm on the measurement).

A means will have to be found to approach the secondary survey points towards the detector, for instance, temporary survey stations on magnet doors, on support tube or attached to the calorimeter. The advantages of this method are versatility of survey action and reduced number of secondary network points. This type of strategy, which requires the redetermination before each measurement of the survey station has the inconvenience of requiring a longer measuring time and preservation of a complete optical access to points of the primary net.

4.2 Comments on Assembly Procedure

The outline of the assembly procedures in "Experimental Area for a High Energy Detector" suggests that the majority of survey work would be done on the surface as an integral part of the assembly sequence of the individual elements of the experiment (magnet, muon detector, hadron calorimeter). A prealignment plus introduction on guide rails should be adopted as often as possible. It would seem useful to improve this simple technique by the permanent inclusion of remote read-out mechanical measuring devices as part of the detector. The establishment of the zero of such devices would be part of the prealignment of the detector and they would provide a continuous measurement of position during and after installation.

The establishment of the internal relationship between physics and survey fiducial marks by industrial triangulation or a calibration bench using alignment telescopes may become part of the assembly process. This discussion must not be treated lightly as it is fundamental to any further survey action on the detector.

4.3 Survey Development and the Next Generation Physics Experiments

The continuing needs of industrial measurement have produced an enormous development in noncontact measurement since L3. The main developments of interest for the alignment of physics experiments are in industrial triangulation, trilateration, total stations and industrial photogrammetry. These methods with some of the key recent developments are briefly described in Appendix A. Industrial photogrammetry seems to be very promising for alignment purposes. It provides a permanent record which can be re-analyzed with hindsight. The precision however is related to object size, the investment in equipment heavy, and it would seem difficult to adapt for use in a reference system (control network points must appear in field of view of camera). Industrial triangulation seems to be the best compromise versatility/measurement time and it provides an on-line redundant

solution. The appearance of precise total station is very interesting because the geometry for theodolite intersections in experimental caverns is rarely ideal. The problem with distance remains the target, the corner cube prism is bulky and unsuitable for angle measurement. The survey group at CERN is looking at the problem, one possibility is to use an adhesive reflective material "scotchlite." This material might produce a sufficient precision (submillimetric) for certain applications.

The problem of the optical medium is finally the limit on the possible precision of industrial survey, the effect can only be minimized by approaching the instrument to the object and by control of the ambient air conditions.

The development of specialized graphical logicals, such as Autocad, are of interest for the preparation works, they should allow the direct inclusion of survey parameters in central drawing banks and make preparation studies in particular modeling of optical paths easier.

4.4 Cost of Survey

The budget for the survey works for the L3 installation was on the order of $350KSF. Ten percent of this budget was for equipment (both new and replacement) and the rest for the temporary manpower required by the installation (up to five student surveyor engineers).

Items which do not appear in this costing include existing equipment and gadgets, the survey group technical support (mechanical workshop, geodetic calibration bench) and the CERN permanent staff who followed the preparation and the installation of L3.

Appendix A. New Trends in Industrial Survey

Industrial Triangulation

Triangulation is the spatial coordination of an object point by intersection of optical rays from two or more electronic theodolites in a common reference system. The optical ray is defined by the horizontal and vertical angles read on the theodolites, the results are normally calculated online.

- New Trends
  - Calibration of theodolites to produce a true solution of 10^{-6} radians.
  - Remote measurement (CCD camera) with remote guidance or automatic image recognition (resolution 2.3 microns).
  - Motorization angular movement of the theodolite (speeds of up to 55° per second).

As a result of this data capture of up to 600 points by hour is now possible, this speed would allow for example the continuous profiling of smooth surfaces.

Trilateration

Trilateration is the spatial coordination of an object point by intersection of distances from three or more distance meters in a common reference system (intersection of spheres).

- New Trends
  - Search for interferometric precision without fringe counting from instrument to object point.
  - Search for high-resolution, but small, corner cubes (robot calibration).

Total Station

A total station produces the spatial coordination of an object point by polar coordinates, optical ray from theodolite plus distance from onboard distance meter.

- New Trends

  - See industrial triangulation and trilateration.
  - Miniaturization to allow inclusion of distance meter in theodolite.
  - Laser tracking systems capable of following object of speed up to 1 m/s (LTS310 KERN & API USA).

Industrial Photogrammetry

A photograph is a two-dimensional image of an object. Coordinates can be measured directly in the plane of the photograph. When a photograph is taken of an object from two different camera positions and viewed through a stereoscope, the overlap between the photographs will appear in three-dimensional models. This three-dimensional model can also be created analytically by digitization of the photograph.

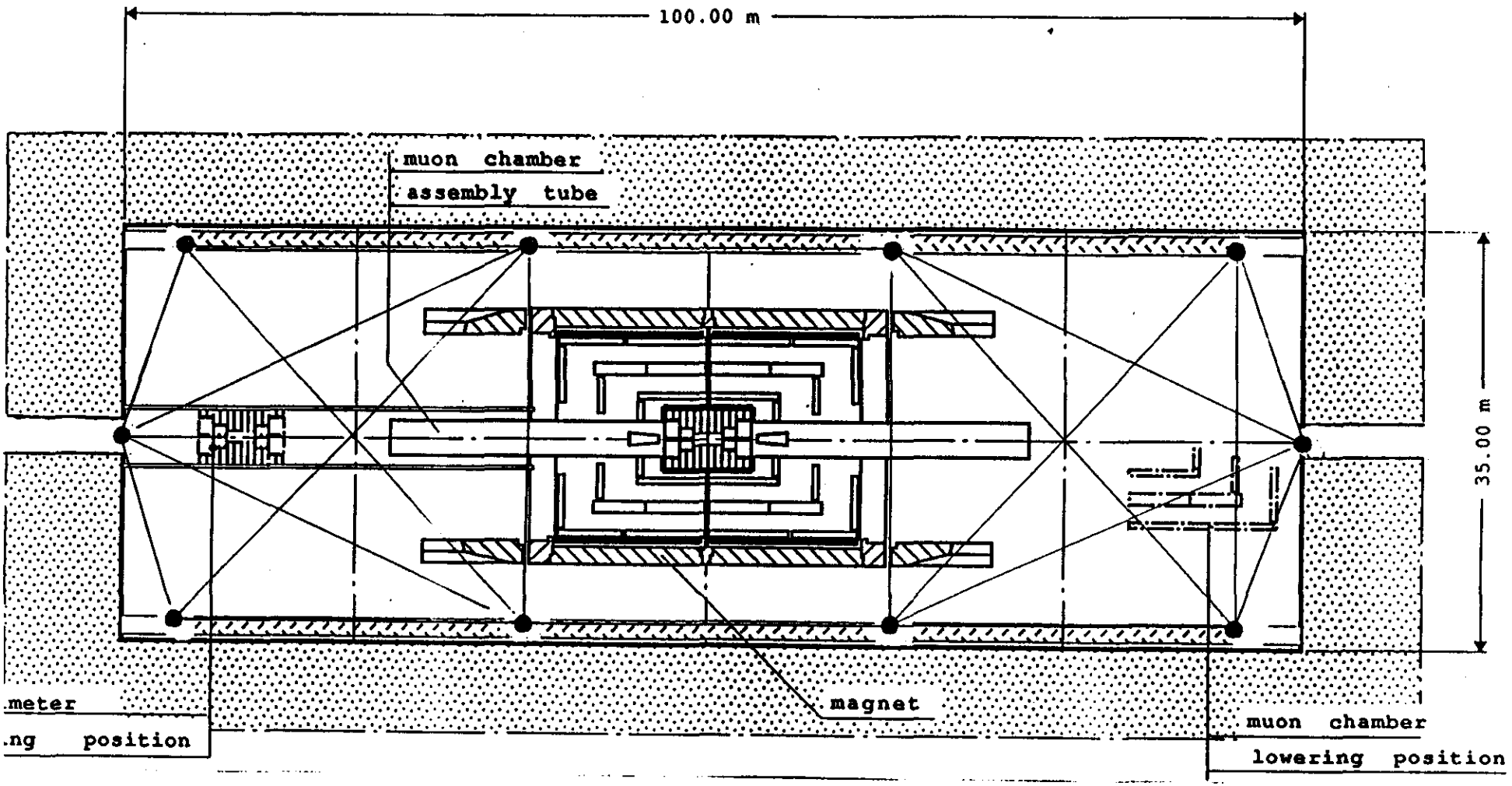

Figure 1 : Primary network indication of possible point positions and optical paths

PROPOSED LHC DETECTOR HALL LAYOUT

Scale 1/500

12.october 1989

ES

PLAN VIEW

095/M4

FIGURE 1