IDM UID
46FN9B
VERSION CREATED ON / VERSION / STATUS
08 Mar 2012 / 2.1 / Approved
EXTERNAL REFERENCE / VERSION

Rules or Handbooks or Guidelines

ITER Dimensional Metrology Handbook

This Metrology Handbook outlines the mandatory requirements for dimensional control of the components, assemblies and systems for the ITER machine. In addition this handbook provides significant guidance and helpful information on best practise for large volume metrology applications which can be used in the production of procurement specifications. The handbook also provides information on the ITER metrology infrastructure and the provision of alignment and metrology services during assembly ...

Approval Process			
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Information Protection Level: Non-Public - Unclassified *RO: Wilson David*			
Read Access	**LG: PCD ext, LG: SIMIC, LG: ITER Project Associate, LG: ADMWG External, LG: M&I ext and Guy, LG: Metrology Ext, LG: Metrology Group, AD: Only-staff, AD: IO_Director-General, AD: External Management Advisory Board, AD: IDM_Controller, AD: Nuclear Safety Inspectors, AD: Auditors, AD: ITER Management A...**		

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Change Log			
ITER Dimensional Metrology Handbook (46FN9B)			
Version	***Latest Status***	***Issue Date***	***Description of Change***
v1.0	Signed	04 Mar 2011	
v1.1	Signed	03 May 2011	Comments included following review
v1.2	Signed	16 May 2011	references to Manual replaced with Handbook +/- 1mm value removed Reference to temperature control requirements added note on MQP requirements added
v1.3	Signed	15 Jun 2011	Following technical review, document issue raised to add reviewers/approver for sign off Authority.
v1.4	Signed	20 Jun 2011	M Kondoh and D Sands added as reviewers at the request of K Blackler
v2.0	Signed	25 Jan 2012	Version for senior management approval after internal review.
v2.1	Approved	08 Mar 2012	Reference to Design Authority Policy removed Hyperlink to SRD 62-13 corrected

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1 Purpose

The purpose of this document is to supply information relating to dimensional metrology to all Departments of the ITER Organisation and Domestic Agencies. To define strategies and infrastructure provision, identify requirements and best practises and provide a standardised approach to dimensional control and alignment processes.

2 Scope

The Dimensional Metrology Handbook (DMH) outlines the mandatory requirements for dimensional control of the components, assemblies and systems for the ITER machine. In addition the handbook provides significant guidance and helpful information on best practise for large volume metrology applications. The handbook also provides information on the ITER metrology infrastructure and the provision of alignment and metrology services during assembly of the machine and its ancillary components and systems.

The DMH is issued as a supplement to project requirements documents, since it is necessary that the requirements contained in this handbook are followed by the ITER Organisation, the Domestic Agencies and industry to ensure the successful construction and operation of ITER.

3 Definitions

Abbreviations and Acronyms

3D	Three Dimensional
A&M	Alignment and Metrology
AIMS	Advanced Integrated Mathematical System
ASCII	American Standard Code for Information Exchange
CAD	Computer Aided Design
CBD	Cryostat Base Datum
CCL	Current Centreline
CCR	Corner Cube Reflector
DA	Domestic Agency
DCM	Design Compliance Matrix
DMH	Dimensional Metrology Handbook
DMIS	Dimensional Measurement Interface Standard
GD&T	Geometric Dimensioning and Tolerancing
GPS	Geometrical Product Specifications
ICD	Interface Control Document
IDM	ITER Document Management System
IGES	Initial Graphics Exchange Specification
IO	ITER Organisation
IS	Interface Sheet
LVM	Large Volume Metrology
MIP	Manufacturing Inspection Plan

MQP	Management and Quality Program
MRP	Mandatory Requirements for Procurement
NRK	New River Kinematics
PA	Procurement Arrangement
PF	Raw 3D Scan data Format
PIF	Parametric Image Format
PIT	Pit Datum
POL	InnovMetric's Binary Format
RO	Responsible Officer
SA	Spatial Analyzer
SAT	Standard ACIS Text
SMR	Spherically Mounted Reflector
SRD	System Requirements Document
STEP	Standardised Exchange of Product
TAD	Tokamak Assembly Datum
TRO	Technical Responsible Officer
TF	Toroidal Field
TFGS	Toroidal Field coil Gravity Support
TGCS	Tokamak Global Coordinate System
VVGS	Vacuum Vessel Gravity Support

4 Communications and acceptance

To satisfy the requirements of this handbook, processes and procedures relating to alignment and dimensional control must be clearly documented and where stated: approved or accepted by the Metrology RO or nominated representative.

Section 11 and its sub-sections "Process control and best practise" identify areas that will be reviewed prior, during and on completion of the activity and will require IO acceptance at predefined stages. *Acceptance/Approval* is to be a positive and recorded action, either by signature or by electronic means.

A possible route of communication and acceptance could be:-

Supplier (Contractor) ↔ Domestic Agency Contract Responsible Officer ↔ ITER Technical Responsible Officer ↔ ITER Metrology Responsible Officer.

5 Alignment and Metrology (A&M) Classifications

Machine components and plant systems requiring alignment and/or dimensional control shall be given an A&M classification by the applicable TRO. The classification shall reflect the importance placed on A&M for the system to function and the consequence of failure on the project. This classification shall be reviewed with the Metrology RO and accepted

Alignment & Metrology (A&M) Class 1

Components or assemblies requiring alignment and/or dimensional control, where failure to comply in these areas will significantly impair or prevent machine assembly and/or operation and could potentially cause schedule delay in excess of one month or cost risk in excess of 1M€.

A&M Class 2

Components or assemblies requiring alignment and/or dimensional control, where failure to comply in these areas will significantly impair or prevent machine assembly and/or operation and could potentially cause schedule delay in excess of one week or cost risk in excess of 0.1M€.

A&M Class 3

No dimensional control oversight by IO is required through the supply chain or on receipt at the ITER site. No component alignment requirements however; setting out points/lines will be required from the IO metrology team to facilitate the installation.

Unclassified

No IO infrastructure required or support from the ITER metrology team

Note: It is the responsibility of the Technical RO to make an assessment of the A&M requirements for his system following the processes in this document in order to determine the A&M class, which is be reviewed by the metrology RO.

6 Mandatory requirements for A&M Tasks

For the ITER machine to operate to specification it is essential that the supply of its constituent parts is controlled throughout their life cycle from raw material through manufacture, assembly commissioning and operation. From a metrology perspective this means that dimensional control processes must be qualified and traceable.

The Metrology RO shall be available to provide technical advice to system ROs during preparation of PAs and Technical Specifications, reviewing metrology related documentation and providing support where necessary during manufacture, assembly/installation and acceptance.

In the following sections, information is provided on best practise guidance for metrology related processes and will be used as the basis for reviewing process documentation relating to dimensional control activities.

Within this section are the mandatory requirements relating to A&M for the supply and assembly/installation of the systems for ITER. If an exceptions to a mandatory requirement is requested it must be agreed by the IO MAI section through a deviation request.

Mandatory requirements relating to A&M are dependent on the A&M classification applicable (section 5) to the component or assembly concerned. These requirements are detailed in the following sub-sections:

6.1 Mandatory Requirements for Site (MRS) based A&M Class 1 activities

A&M Class 1 activities are critical to the successful assembly/installation and operation of the ITER machine and as such require the highest level of qualification and control. Listed below are the mandatory requirements, as applicable for the system concerned, identifying responsibilities for their delivery and acceptance. The Metrology RO or his delegate shall review all key documents pertaining to A&M tasks within this classification.

[MRS1] The System Requirements Document (SRD), Interface Control Document (ICD) or other document, shall define the alignment and/or dimensional control requirements. These shall be included in the DCM and the methods to achieve them shall be reviewed and approved as part of the ITER Design Review Procedure with the Metrology RO accepting the process for the A&M tasks.

[MRS2] The ITER RO shall identify all A&M quality documentation that will form part of the supply for the applicable system. The dossier of documents shall be certified compliant with the requirements of the technical specification or shall be supported by a non-conformance report. This shall be in place prior to any A&M work commencing at the ITER site.

[MRS3] For items requiring goods inwards, in-process or final inspection, a list of key characteristics shall be compiled by the RO to identify the scope of the inspection. Datums and tolerances shall be identified in a drawing or other medium acceptable to the inspection team carrying out the task. A method statement or procedure shall be prepared by the party responsible for the inspection which shall be accepted by the Metrology RO or his delegate.

[MRS4] For items requiring setting out, pre-alignment and/or final alignment at the ITER site, a procedure shall be prepared detailing the requirements, process description, reference data, output data together with reporting and acceptance criteria. This procedure shall be accepted by the Metrology RO or his delegate prior to task commencement.

[MRS5] The coordinate/datum systems used during inspection and alignment tasks on the ITER site shall be clearly defined in the A&M procedure for the task and applicable drawings. Where datums evolve to reflect as-built variation in the assembly/installation process the logic shall be traceable back to the nominal requirement.

[MRS6] Inspection reports shall identify the nominal dimensions, applicable tolerances and the dimension achieved for the feature, with non-complying values flagged in red on the report. These features shall be the subject of rework or a non-conformance report.

[MRS7] All metrology equipment used for A&M tasks shall hold a current calibration certificate issued by an accredited laboratory (Reference standard BS EN ISO/IEC: 2005). The equipment selected by the supplier shall be fit for the requirements of the measurement process considering areas such as: measurement uncertainty, speed of data acquisition, measurement geometry, local environmental conditions etc.

[MRS8] Measurement uncertainty shall be calculated for all reported measurements at a confidence level of 2σ. As a general rule, the uncertainty value shall not exceed 20% of the tolerance applicable to the feature measured. Maintaining an uncertainty of 10% or less is recommended to optimise the available tolerance applicable to the feature concerned.

[MRS9] The IO drawings specify dimensions at the reference temperature of 20˚C. The environmental conditions for A&M will depend very much on the location in which the activity is to be carried out. The RO shall make an assessment of the impact of thermal expansion/contraction on the A&M task and specify controls to be put in place as necessary to compensate. Consideration shall be given to the thermal inertia of the components being measured, where necessary allowing sufficient soak time in the measurement environment to ensure thermal stabilisation. For critical items Temperature measurements (better than ± 1°C) shall be recorded throughout the measurement task of both the component and the environment, logged against time and saved with the measurement file. For large components, multiple measurements shall be required to enable the detection of thermal gradients.

[MRS10] For measurement surveys utilising multiple instrument stations, bundle adjustment algorithms shall be utilised to ensure error propagation, via multiple best-fit alignments, does not occur.

[MRS11] All “as-built” drawings/3D models/electronic data shall be supplied in a format agreed with the IO to demonstrate compliance with the design. The IO does not prescribe which software should be used however; it is critical that measurement data can be easily transferred been all parties requiring access to it.

[MRS12] All inspection/dimensional control and alignment reports shall include, as a minimum, the following information:

- Identification of measuring instruments used including calibration certificate number
- Identification of ancillary equipment, as applicable, used including type, make unique identifier and calibration certificate number i.e.
    - Test unit
    - Probes (dimensions, frequencies)
    - Targets and tooling

    - Scale bars
- Identification of the part examined
- Reference drawing or CAD model identification defining the tolerances, datum etc. which the part has been inspected to, including issue status
- Time and place of the inspection plus signature of the operator
- Name and qualification of the operator and his employer.
- Procedure followed and issue status
- Meteorological data (temperature, humidity, pressure)
- Identification of all computer files generated during the inspection, all raw and processed data must be in a format acceptable to the IO
- Written values tabulated to provide: nominal dimensions, applicable tolerances and the dimension achieved for the feature, with non-complying values flagged in red on the report. Graphical data may be used if agreed by IO.
- Interpretation of results, including an explanation for any readings considered invalid.
- Identification of any non-conformity reports raised.

[MRS13] All drawings and/or electronic data used for A&M activities shall be issued through the ITER document control process and certified at the status to which they shall be used.

6.2 Mandatory Requirements for Site (MRS) based A&M Class 2 activities

Components or assemblies with an A&M class 2 will require a significant amount of dimensional control on the IO site. They may need to go through a pre-alignment process to provide references (fiducials) for assembly/installation and may also need inspections during and on completion of assembly/installation.

A&M class 2 tasks however have a reduced impact on cost and schedule in the event of failure therefore requiring a reduced level of input by the Metrology RO.

The A&M class 1 mandatory requirements [MRS1] through to [MRS13] shall be maintained for this classification, as applicable to the task, but the requirement for review/approval by the Metrology RO is removed.

6.3 Mandatory Requirements for Site (MRS) based A&M Class 3 activities

A&M class 3 activities only require setting out points/lines to facilitate their installation therefore the mandatory requirements for these activities are [MRS4], [MRS7] and [MRS13].

6.4 Mandatory Requirements Procurement (MRP) for A&M Class 1 activities

A&M Class 1 activities are critical to the successful assembly/installation and operation of the ITER machine and as such require the highest level of qualification and control. Listed below are the mandatory requirements, as applicable for the system concerned, identifying responsibilities for their delivery and approval. The Metrology RO or his delegate shall be given the opportunity to review all key documents pertaining to A&M tasks within this classification.

[MRP1] The System Requirements Document (SRD), Interface Control Document (ICD) or other document, shall define the alignment and/or dimensional control requirements relating to the subject of the procurement. These shall be included in the DCM and shall be reviewed as part of the ITER Design Review Procedure.

[MRP2] The A&M requirements for the procurement shall be included within the Technical Specification (Annex B for PA's) with design drawings and associated design documents defining the fundamental design dimensions and tolerances. The supplier shall produce shop floor documentation that demonstrates how the manufacturing and/or assembly process shall be controlled throughout the production cycle. This shall include tolerance requirements for relevant stages of the manufacturing process that shall be agreed with the IO prior to commencement of manufacture.

[MRP3] Prior to contract commencement the supplier shall produce an implementation plan defining all quality related activities to be carried out during the contract. Elements relating to A&M shall include:

- Reference standards
- Design change control procedures – Drawings and CAD models
- Document control
- Instrument calibrations and test procedures
- Control of non-conformities
- Data management procedures
- Measurement procedures- data acquisition, post processing and validation
- Reporting procedures

The Metrology RO shall be given the opportunity to review the implementation plan and any documents referenced within it, prior to contract commencement.

[MRP4] Inspections shall be carried out at all crucial stages of the manufacturing process to guarantee adherence to final tolerances and set as early as possible corrective measures where necessary. The frequency and details of these inspections shall be defined by the supplier in the MIP for the procurement which the IO will be given the opportunity to witness at their discretion.

[MRP5] The coordinate/datum system used during inspection and dimensional control processes shall be as defined in the design drawings. Inspection reports shall identify the nominal dimensions, applicable tolerances and the dimension achieved for the feature with non-complying values flagged in red on the report.

[MRP6] All metrology equipment used for A&M tasks shall hold a current calibration certificate issued by an accredited laboratory (Reference standard BS EN ISO/IEC: 2005). The equipment selected by the supplier shall be fit for the requirements of the measurement process considering areas such as: measurement uncertainty, speed of data acquisition, measurement geometry, local environmental conditions etc.

[MRP7] The supplier shall draft a dimensional control plan (DCP) that shall include all inputs and outputs relating to the measurement process, see section 9. The DCP shall be supplied to the IO for acceptance, prior to commencement of manufacture.

[MRP8] Measurement uncertainty shall be calculated for all reported measurements at a confidence level of 2σ. As a general rule, the uncertainty value shall not exceed 20% of the tolerance applicable to the feature measured. Maintaining an uncertainty of 10% or less is recommended to optimise the available tolerance applicable to the feature concerned.

[MRP9] The IO drawings specify dimensions at the reference temperature of 20˚C. Dimensional control for factory acceptance shall be carried out in a controlled environment with a maximum temperature variation of ± 2˚C. Key dimensions shall be measured at the reference temperature or corrected to this temperature therefore temperature stability during the measurement process is critical. Raw measurement data and corrected values shall be made available to the IO. Consideration shall be given to the thermal inertia of the components being measured allowing sufficient soak time in the measurement environment to ensure thermal stabilisation. Temperature measurements (better than ± 1°C) shall be recorded throughout the measurement task of both the component and the environment, logged against time and saved with the measurement file. For large components, multiple measurements shall be required to enable the detection of thermal gradients.

[MRP10] For measurement surveys utilising multiple instrument stations, bundle adjustment algorithms shall be utilised to ensure error propagation, via multiple best-fit alignments, does not occur.

[MRP11] The supplier shall produce "as-built" drawings/3D models/electronic data, in a format agreed with the IO demonstrating compliance with the design. The IO does not prescribe which software should be used however; it is critical that measurement data can be easily transferred between the parties to the ITER agreement. During manufacture this data may be required to qualify measurement processes, address non-conformance issues, and consider concession requests. In addition, the data may be used to construct a configuration model representing the true geometry of the item concerned.

[MRP12] Deviations from the design requirements shall be the subject of a non-conformance (NCR) report with corrective measures involving geometric or material property changes requiring the prior approval of the IO. To enable a decision to be made the supplier shall furnish the IO with documents justifying their proposal delivered within the NCR system.

[MRP13] All inspection/dimensional control reports shall include, as a minimum, the following information:

- Identification of measuring instruments used including calibration certificate number
- Identification of ancillary equipment, as applicable, used including type, make unique identifier and calibration certificate number i.e.
    - Test unit
    - Probes (dimensions, frequencies)
    - Targets and tooling
    - Scale bars
- Identification of the part examined
- Reference drawing or CAD model identification defining the tolerances, datum etc. which the part has been inspected to, including issue status
- Time and place of the inspection plus signature of the operator
- Name and qualification of the operator and his employer.
- Procedure followed and issue status
- Meteorological data (temperature, humidity, pressure)
- Identification of all computer files generated during the inspection, all raw and processed data must be in a format acceptable to the IO
- Written values tabulated to provide: nominal dimensions, applicable tolerances and the dimension achieved for the feature, with non-complying values flagged in red on the report. Graphical data may be used if agreed by IO.
- Interpretation of results, including an explanation for any readings considered invalid.
- Identification of any non-conformity reports raised

In order to avoid unnecessary duplication, some of the information listed above can be provided in documents identified by the supplier and attached to the report.

6.5 Mandatory Requirements Procurement (MRP) for A&M Class 2 activities

Components or assemblies with an A&M class 2 for procurement will require a significant amount of dimensional control during manufacture, overseen by the IO. They may need to go through a pre-alignment process to provide references (fiducials) for assembly/installation at the ITER site and may also need some form of inspection during factory acceptance or on receipt by the RO.

The TRO for the system involved shall need to consider the level of control to be applied during the procurement process and identify the mandatory requirements in the technical specification applicable to the procurement.

As a minimum the following mandatory requirements from A&M class 1 shall be applied: [MRP1], [MRP2], [MRP3], [MRP4], [MRP5], [MRP6], [MRP7] and [MRP12]. Other requirements may be added at the discretion of the RO.

Note: Components of A&M Class 3 or below require no specific dimensional controls of alignment activities during the procurement process.

7 Standards

There are a large number of standards relating to dimensional metrology which can broadly be grouped under the scope of two Technical Committees within the International Standards Organisation (ISO) namely:

TC 213 - Dimensional and geometrical product specifications and verification

> Standardisation in the field of geometrical product specifications (GPS), i.e. macro- and microgeometry specifications covering dimensional and geometrical tolerancing, surface properties and the related verification principles, measuring equipment and calibration requirements including the uncertainty of dimensional and geometrical measurement. The standardisation includes the basic layout and explanation of drawing indications (symbols).

TC 176 - Quality management and quality assurance

> Standardization in the field of quality management (generic quality management systems and supporting technologies), as well as quality management standardization in specific sectors at the request of the affected sector and the ISO Technical Management Board.
>
> *Note:*
>
> ISO/TC 176 is also entrusted with an advisory function to all ISO and IEC technical committees to ensure the integrity of the generic quality system standards and the effective implementation of the ISO/IEC sector policy on quality management systems deliverables.

Non ISO standards useful for reference:

Guidelines for the Evaluation of Dimensional Measurement Uncertainty (Technical Report) (B89.7.3.2 - 2007)

Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems (B89.4.19 - 2006)

8 Infrastructure - Survey Networks and datums

All measurement tasks need a fixed reference base (the datum) from which measurements can be made and calculated. For large volume metrology (LVM) applications this reference typically takes the form of a survey network consisting of a collection of target nests and/or instrument stations of known geometry and computed uncertainty.

The accuracy and precision of the survey network(s) directly affects the measurement accuracy that can be achieved for subsequent alignment tasks. Accuracy and precision are terms that often get confused therefore for the purposes of this document their definitions are as follows:

Accuracy:	The degree of conformity of a measured or calculated quantity to its actual (true) value
Precision:	The degree of repeatability achieved when the same quantity is measured a number of times

The survey network design process starts with a specification detailing how the network will be utilised and defining the ultimate measurement tolerances to be achieved. A perfect measurement does not exist therefore it is important to be able to determine the measurement uncertainty for each stage of the measurement process and thus create a tolerance budget.

Measurement uncertainty:	The parameter, associated with the result of a measurement (e.g. a calibration or test) that defines the range of values that could reasonably be attributed to the measured quantity. When uncertainty is evaluated and reported in a specified way it indicates the level of confidence that the value actually lies within the range defined by the uncertainty interval.

The survey networks for ITER will cover the whole of the site, providing a global coordinate matrix for survey instruments to reference against. The accuracy requirements for each network will vary, dependent on the alignment tasks for which they are being supplied. As such, interface control documents need to clearly define the alignment requirements of ITER components, assemblies and systems.

8.1 Primary Survey Network

The first survey network installed was the Primary Survey network which defines the site reference system for buildings construction, provides the datum for monitoring stability and is the global datum for dedicated secondary networks installed throughout the site.

The network consists of a collection of geodetic pillars, spread around the site and tied into foundations designed to optimise stability. A common interface for force-centring survey instruments and survey targets is embedded in the top of each pillar.

The network was installed and measured in the summer of 2010. A least squares adjustment was made to optimise the network and determine the co-ordinate and uncertainty values for each survey monument. The measurement uncertainty for the network was calculated to be ~1mm when initially measured. The network will be periodically monitored for stability.

The coordinates of the primary survey network are reported within the Lambert III mapping projection with elevations relative to sea level. The Tokamak Global Coordinate System (TGCS) is an orthogonal system with the gravity vector defining the Z-axis at machine centre, the Y-axis points towards site north (37˚ counter-clockwise from geographic north) with the X-axis mutually perpendicular to Z & Y in an easterly direction. The origin of the coordinate system is at the nominal tokamak centre. For more information on ITER co-ordinate systems refer to document ITER_D_2A9PXZ.

8.2 Tokamak Pit Network

Machine assembly activities within the tokamak pit shall require accurate and precise alignment of components. The design specification for the network is to achieve an uncertainty no greater than ± 0.2 mm within a temperature controlled environment of ± 2˚C (ref. SRD 62-13), this requirement is achievable if the environment remains stable. However, it is clear that with the immense transfer of loads occurring during construction that the network will move and distort to a certain extent. This distortion will need to be monitored and modelled during machine assembly to ensure that the final machine is aligned to specification. Both dynamic and passive measurement systems are being considered to provide an efficient system for monitoring the network movement and thus enable adjustments to be calculated and employed.

The initial network shall consist of many targets, or target nests, distributed around the pit wall covering the full height of the pit and extending into the adjacent port cells. The best fit centre of the pit shall be derived from the pit wall targets defining the vertical datum axis for machine assembly. The datum for toroidal position and elevation will be derived from the best fit position of the port cells.

Once the lower cryostat cylinder is installed, lines of sight to the lower pit wall targets will be blocked however, lines of sight from the pit into the port cells and vice versa shall be maintained. The pit wall targets above the cryostat lower cylinder shall remain visible throughout the vacuum vessel construction, only becoming obscured when the cryostat upper cylinder is installed. The port cell targets are very important to the pit network as they provide the link to systems external to the pit within the adjacent galleries.

It is likely that a number of different instrument types will be used during the tokamak build process such as photogrammetry cameras, laser trackers and total stations. Laser trackers and total stations measure to similar spherically mounted reflectors called SMRs or corner cube reflectors CCRs, different names for the same item. Photogrammetry uses retroreflective however, common targeting mounts are readily available from suppliers such as Hubbs and Brunson enabling interchangeability of instruments utilising the network.

8.3 Tokamak Galleries Networks

Survey networks shall be installed external to the bio shield wall within the port cells and galleries. These multi-level networks shall provide the dimensional control for all systems external to the tokamak pit within the tokamak building and will be linked to the Tokamak Pit Network via the port cells. The network shall consist of a collection of wall and floor mounted target nests distributed throughout the galleries. These will be a standardised design as used for the pit network thus allowing flexibility of instrument selection for measurement tasks.

Provision shall be made to link the tokamak hall network to the primary network. This will be carried out with a total station and level and will be periodically checked for stability whist lines of sight remain available.

8.4 Generic Buildings Networks

There are various buildings around the site having different requirements for dimensional control. Users of these buildings need to consider their requirements at an early stage so that fit for purpose networks can be installed and measured in a timely manner.

Where required, building networks shall be linked to the primary survey network thus providing a global position for all setting out, alignment and measurement tasks. Where a local reference is required co-ordinate transformations into the building co-ordinate system can be made (ref. ITER_D_2A9PXZ).

8.5 Assembly Datums

During assembly of the ITER machine it will be necessary to adjust the build datum to optimise the assembly process with respect to the as-built geometry of key machine components. Each build datum shall define the position and orientation of a coordinate frame within which the coordinates of the targets/target nests of the Tokamak Pit Network shall be valued.

The pit datum (PIT) as described in section 8.2 will be the initial datum used to align the following components:

- Cryostat Column Baseplates
- Cryostat Columns
- Cryostat Base Section assembly

The as-built position of the cryostat base shall be used to define the cryostat base datum (CBD) this shall be used to align:

- Cryostat lower Cylinder
- TF Coils

The key characteristics on the cryostat base that are used to establish the CBD are the gravity support interfaces for both the TF coils (TFGS) and the vacuum vessel (VVGS).

The key characteristic of the coils to be aligned is the current centre line (CCL) of the winding back, its position defined with respect to fiducials on the coil case.

When the 18 TF Coils are in place, the Tokamak Assembly Datum (TAD) shall be established representing the Least Square best Fit of the 18 TF Coils. This datum shall be used for final alignment of the vacuum vessel, remaining magnet systems and the internal vacuum vessel components.

9 Survey and Alignment during buildings construction

During the construction phase of the ITER buildings there will be many requirements for accurate alignment. ROs need to carefully consider the alignment requirements of their systems especially in areas of restricted access where opportunities to define reference points may be limited.

The alignment path of systems that will ultimately be separated by physical barriers, such as concrete walls, may not be restricted at an early stage of the project. Providing the alignment references at this early stage may be the only opportunity to carry out the task and therefore guarantee the success of the installation.

Some large or heavy pieces of plant and equipment may have to be installed during the construction process if access to deliver such component will not be possible once construction is complete. In these instances, alignment references will need to be established in advance to facilitate the setting out and alignment as required.

Generally speaking; if a piece of equipment needs to be installed accurately to a global co-ordinate i.e. not positioned to local features like adjacent walls, building columns etc., then access to a survey network or pre-defined and established reference points will be required. Local alignment tasks need clear lines of sight or a network or dedicated reference points to facilitate the task.

The installation of the primary survey network is complete however the addition, pace and sequence of secondary networks will be driven by the requirements defined by the various system ROs on the project and should be clearly defined in the project schedule.

10 Design for Alignment and Metrology

The ITER machine is made up of many complex components and assemblies which need to interact in specific ways for the experiment to be successful. The design process will identify the optimum configuration for these systems identifying key characteristics to be focussed on with realistic parameters for manufacture and assembly, achieving a fit for purpose design.

From a metrology perspective, measurement uncertainty is a key contributor to the overall tolerance budget and as such needs to be carefully considered. For example; if a component can be manufactured to a perceived tolerance of +/- 1 mm but the measurement process can only deliver to +/- 2 mm then the overall process is clearly out of control.

It has already been identified that survey networks can be designed and installed to provide the datum for alignment activities. This however is only part of the requirement; the components themselves also need to be equipped with alignment features, designed to interface with the most appropriate measurement instruments and positioned to deliver the required alignment accuracy. In addition, the survey features need to be positioned with due consideration to the kinematics of the alignment system. There is no point in having an accurate and precise measurement system if the alignment mechanism cannot respond efficiently to the data provided by the measurement survey.

The list below identifies areas for consideration when designing components for alignment:

Alignment tolerances

- Position
- Elevation
- Angle: Roll, Pitch,
- Yaw

Datum references

- PIT
- CBD
- TAD
- Local to component

Alignment features

- Target nests
- Tooling Ball
- Retroreflective targets
- Scribed reference lines

Adjustment Mechanisms

- Screw threads
- Jacks
- Cams

Alignment Geometry

- Plane
- Line
- Centre of rotation
- Coupled or decoupled

Metrology Instruments

- Laser Trackers
- Total Stations
- Theodolites
- Articulated measurement arms
- Photogrammetry
- Laser Scanners
- Levels

During the design and planning stages for ITER and in support of the procurement arrangements (PAs), the Metrology RO is available to give advice on aspects relating to geometrical and dimensional control for the project. Inspection and alignment surveys can be simulated at the design stage enabling qualification of measurement processes and the determination of uncertainty values for measured points and features within the survey.

11 Process control and best practise

The control of dimensional measurement is an essential part of the supply chain for the ITER components and the subsequent assembly activities to be carried out at the ITER site. For all critical inspections/surveys the measurement process needs to be clearly defined, controlled and accepted by the IO.

Inputs to the process may include:

- design specifications, drawings, CAD models
- quality plans, procedures, method statements
- measuring instruments, calibrations, reference artefacts
- components and assemblies
- plant and equipment
- personnel, skills, training
- computer software, simulations, uncertainty analysis

With outputs such as:

- raw measurement data
- Meteorological corrections
- Scale adjustments
- co-ordinate frame transforms
- quality control inspection reports
- best-fit analyses and transformation matrices
- aligned component / assemblies
- fiducially referenced components / assemblies
- survey uncertainty analyses
- signed off method statements, procedures, quality plans
- Survey Report

The measurement process needs to be fit for purpose; delivering the required outputs in an efficient manner and providing assurances that the process is under control. The IO shall be given the opportunity to review the process documentation prior to commencement and to witness inspections/surveys during manufacture, hold points shall be specified in the Manufacturing and inspection Plan (MIP) as required. In exceptional circumstances the IO reserves the right to carry out its own dimensional control measurements utilising its own personnel or a third party supplier.

The IO shall identify key interfaces which must be inspected during manufacture and monitored during assembly operations, such as welding, which may affect the fit, form or function of the assembly. The control of such operations shall be clearly defined in the process documentation with measurement data recorded in an appropriate format.

11.1 Large volume portable measurement systems

For large volume metrology it is often necessary to bring the measuring instrument to the job. Portable co-ordinate measurement systems such as Laser trackers, total stations, theodolites and photogrammetry, enable the surveyor/inspector to carry out the measurement task in the workplace however, with this flexibility comes added variables that must to be controlled.

The workshop environment is unlikely to be as rigorously controlled as a dedicated metrology lab. Changes in temperature, humidity and pressure all contribute to measurement variance and therefore need to be recorded and compensated for.

Measuring a large component or assembly will often require the use of multiple instrument stations. This may be due to line of sight constraints or as a means of reducing observation lengths within the survey to minimise measurement uncertainty. Whatever the reason, if the results are to be considered within a single coordinate system then a network solution to the fit will be required. Best practice is to carry out a bundle adjustment of the network; this iterative process will optimise the network by minimising the combined pointing errors of the measurements. With the instrument stations optimised the uncertainty of the measured points within the network can be calculated through a variance algorithm.

Minimising the potential for error will come from a good understanding of the technical specification, consideration and compensation for the working environment and by applying best practice processes.

11.2 Best-fit analysis and alignment transformations

Initial measurements taken during a survey will be valued within the measuring instrument’s local co-ordinate system. Their relationship to each other will be clearly defined but they will require aligning to the part or assembly to which they relate.

The alignment can be defined by geometry measured within the measurement session i.e. points, lines and planes or by referencing measured points to features within the CAD model such as faces, surfaces etc.

Unlike the CAD model, the measured points will not fit perfectly to the design nominal therefore a series of weighted best-fits will need to be applied to optimise the alignment. The IO shall identify the key characteristics to be used for the alignment and prioritise their importance. This information shall either be provided within engineering drawings, annotated to the CAD model or as written instructions.

The supplier's measurement procedure shall identify best fit processes to be carried out including any data filtering that will be applied. In general, all raw data shall be maintained and stored for ease of recall and review by the IO.

11.3 Control of inspection measurement and test equipment

All measuring equipment must be fit for purpose to deliver to the tolerances specified. A documented calibration system must be in operation traceable to national standards and certificated through an accredited body. A calibration schedule must be in place with all calibrations logged within a register and all calibration certificates filed for ease of recall.

A Quality document shall clearly identify where and when measurement equipment has been used. Each piece of equipment shall be uniquely identified and must only be used when its calibration status is within date.

For critical measurements it may be necessary to calibrate a measuring instrument more frequently than the suppliers recommended interval. Where the IO deems this necessary it shall mark up the quality plan accordingly.

11.4 Coordinate systems and measurement units

In general, when conveying results of a survey/inspection the co-ordinate system used shall be coincident and of the same type as that used to specify the design. The measurement units shall be as defined in the drawing or model and the deviation from nominal of the as-built dimensions shall be reported in the same manner as they are toleranced.

Results from an inspection shall be expressed in quantative terms when a design characteristic is expressed in numerical units. Attribute data may be used (e.g. go/no-go) if no inspection technique resulting in a quantative measurement is feasible. Where this is the case the gauge used for the process shall be traceable to an appropriate national standard.

11.5 Metrology software and data formats

The ITER organisation has adopted Spatial Analyzer (SA), supplied by New River Kinematics (NRK), as its preferred metrology software. The software interfaces with the vast majority of measurement instruments; its architecture maintains full traceability of the measurement process storing all raw measurement data and environmental monitoring corrections.

The software has been specifically designed for large volume metrology applications; its optimisation algorithms for network configurations, computes measurement uncertainty by default and analyses instrument performance in the process. The system can be used offline for measurement simulations by utilising constructed geometry within the application or by directly importing Catia V5 models, complete with embedded GD&T if required.

The IO does not prescribe which software should be used however; it is critical that measurement data can be easily transferred between the parties to the ITER agreement. During manufacture this data may be required to qualify measurement processes, address non-conformance issues, consider concession requests and certainly to build up as-built models of the supply.

The following data formats can be read into SA:

ASCII, STEP, IGES,VDA, SAT, DMIS, AIMS-TDF, Polyworks (POL, PIF, PF, DPI), Direct Catia V4 V5 *.CGR process, Direct UG process, Direct ProE process, VSTARS .xyz file, VSTARS Cameras (outstar.txt), xyz ijk File (IJK), Digital network levels, IMETRIC, 1-D data (Datamyte).

In all cases measurement data must include uncertainty values, see following section.

11.6 Measurement uncertainty

Measurement uncertainty is the parameter, associated with the result of a measurement (e.g. a calibration or test) that defines the range of values that could reasonably be attributed to the measured quantity. When uncertainty is evaluated and reported in a specified way it indicates the level of confidence that the value actually lies within the range defined by the uncertainty interval.

No measurement is complete unless its uncertainty can be quantified. In a similar way that a tolerance relays the acceptance specification for a given dimension, the measurement uncertainty must be considered when determining whether a measured characteristic meets the design criteria.

For example: if the distance between 2 points is required to be 10m +/- 0.003m then a measurement returning a value of 10.0025m appears to be acceptable however; if the measurement uncertainty for each point is +/- 0.001m then the reality is that the measured dimension could be out of spec by up to 0.0015m.. Figure 1 demonstrates this pictorially

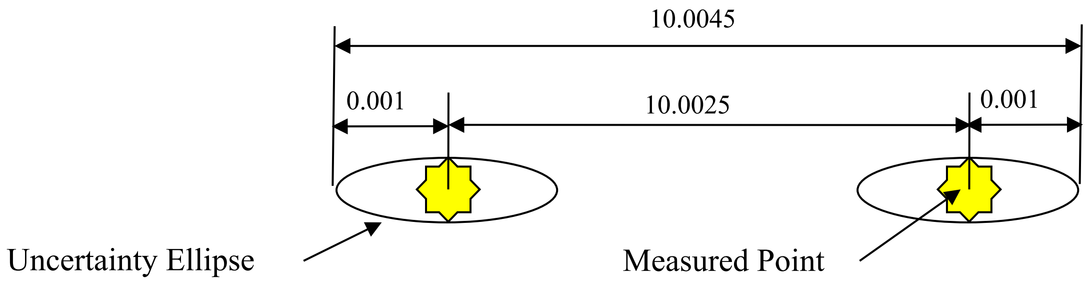

Figure 1: example of an uncertainty analysis for a linear dimension

11.7 Measurement scale

Components for the ITER machine are dimensioned nominally at 20˚C. For large objects the effects of temperature change on the physical size of the object can be considerable and as such must be taken into account during the measurement process.

Measurements, especially those carried out over a prolonged period, must be carried out in thermally stable conditions. The measuring instrument and component must be given time to acclimatise to the environment and the temperature must be monitored throughout the measurement task.

Where the measurements cannot be taken at 20˚C a scale factor will need to be applied to the measurement job. In consideration of the components orientation and fixturing, the scaling vector(s) shall be identified in the measurement plan for acceptance by the IO.

When using optical measuring systems such as laser trackers or total stations consideration needs to be given to distance measurements from these instrument's interferometers or absolute distance meters. Environmental factors such as changes in atmospheric pressure, temperature and humidity will affect the wavelength and as such need to be corrected. All environmental monitors used for this process must be calibrated in line with the manufactures recommendations and traceable to national standards.

Intersecting theodolite systems and photogrammetry rely on defined calibrated length measurements to scale the measurement job. Scale bars, interferometer measured distances or a controlled and traceable network of stable points can all be used to introduce scale. The important factor is that the scale system is controlled, fit for purpose and traceable.

11.8 Component orientation and fixturing for measurement

There are many large and heavy components which are assembled together to make the ITER machine. These components will distort to varying degrees depending on how they are supported during manufacture and assembly therefore it is essential that these parameters are considered and clearly defined within the measurement procedure.

Where a component is to be supported, machined and inspected in one orientation but put into service in another, the effects of the transformation need to be established.

By default, CAD models describe a components shape and size in a state of equilibrium, unaffected by external influences such as gravity. Computer added manufacturing and inspection systems often use the CAD model to drive the manufacturing and inspection processes therefore the CAD model either needs be morphed to reflect the geometric condition for inspection or offset values need to be supplied for the specific areas of interest.

11.9 Fiducialisation

Fiducialisation is the process used to define reference points (fiducials) on a component or assembly with respect to a reference coordinate frame. The position and orientation of the frame is constructed from as-built measurement data and reflects the optimum alignment achievable from the data set measured.

To define an object's 3D position and orientation, a minimum of 3 fiducials are required however, utilising more fiducials will add redundancy to the survey and provide a better representation of the measurement volume. The quantity and position of the fiducials will be driven by the design specification and qualified through tolerance assessment and uncertainty analysis.

Where fiducials are required to facilitate an alignment at the ITER site, their design, position and orientation will be defined by the IO. Fiducials used by the supplier shall either be permanently attached to the object or fitted temporarily during the measurement via a standard interface as descried in section 11.10.

11.10 Targets and tooling

Laser trackers and total stations measure to similar spherical targets called SMR retroreflectors or corner cubes. Photogrammetry also uses retroreflective targets but of a different type however, interchangeable targeting mounts are readily available.

A typical interface for these mounts could be an H7 hole of diameter 6, 8, or 10 mm reamed perpendicular into a reference face. The important thing to note is that whilst the mount will position the target coincident with the axis of the hole, the target will be offset from the reference face by a defined amount.

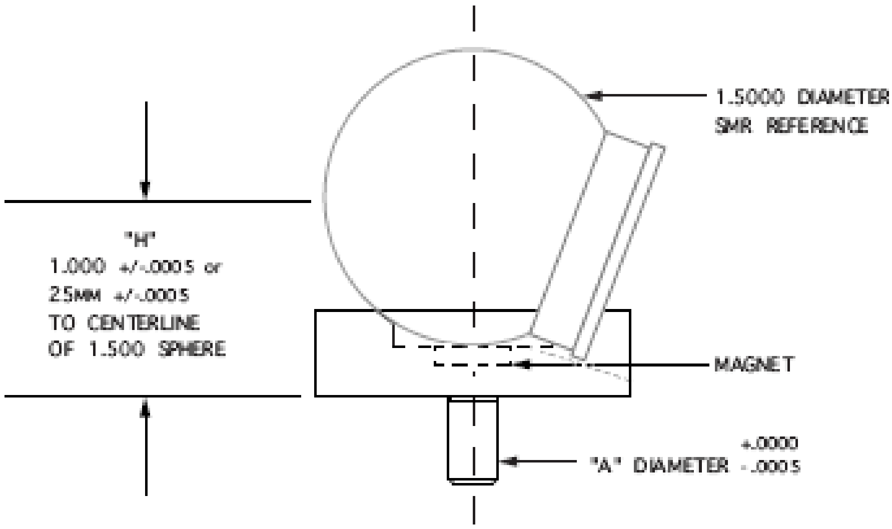

Fig. 1 Example of an SMR mounted in a pin nest

The example above shows a laser tracker SMR retroreflector mounted within a target mount. Dimension “H” identifies the offset applied and the manufacturing tolerance.

All targeting mounts or generically speaking tooling, that contributes to the measurement process shall be controlled within the supplier’s calibration system and shall be uniquely identified. The measurement process shall specifically record when such tooling has been used defining the offset applied and its direction.

12 Coordination for metrology activities

Many of the components for the ITER machine have extremely demanding tolerances with respect to alignment and dimensional control. Their installation locations are often very constrained and their large size makes adjustment all the more difficult. These components may be standalone items or an embodiment of constituent parts combined to deliver a specific function. Whatever the requirement, if metrology is a contributor then it is an interface that needs to be resourced and managed.

The Metrology RO is available to give technical advice during the design phase of the project and is tasked to put in place and manage the requisite infrastructure to support the machine build and its associated systems. This will include the design and realisation of survey networks (section 8) development of alignment strategies, procurement of equipment and the day to day management of the metrology team.

The ITER metrology team shall be assembled to support the programmed metrology requirements of the ITER project therefore it is important that these needs are identified as early as possible to optimise the resourcing with respect to equipment and personnel.

12.1 Interface control

ROs for components, assemblies and systems requiring support from the ITER metrology team shall specify their requirements in an appropriate technical document i.e. SRD, ICD, dedicated IS.

Typical details required shall include:

- General description of the measurement task detailing processes and required outputs
- Reference datum systems to be used i.e. site primary datum system, pit datum system, locally defined system etc.
- Tolerance requirements for dimensional control and or alignment i.e. position angularity, elevation, level etc.
- Fiducialisation requirements (section 11.9)
- Location where the survey / inspection is to be carried out
- Scheduled date for the task and sub-tasks
- State of plant during the task(s); component orientation, supporting structures, scaffolding, adjacent work activities etc.
- Environmental controls envisaged during the survey

From the above information the Metrology RO will elaborate a measurement plan, detailing the work scope, equipment and tooling requirements, estimated task duration and manpower allocation. Any inputs required from the customer such as drawings, CAD models etc. will be identified and their required delivery dates included in the metrology schedule.

The ITER ‘Assembly and Installation Management Manual’ details the processes and procedures to be followed in preparation for and during implementation of assembly and installation activities. Reference 3 of the document details the ‘System Assembly Compatibility Assessment Procedure’ this procedure will be used by the Machine Assembly and Installation Section to assess compliance with assembly methodologies and standards and to determine readiness for development of assembly operating procedures. Appendix 1 to the document ‘ITER System Assembly Compatibility Assessment Form’ includes an input table specific to metrology activities; ‘Table 6: Dimensional control and Alignment’. This table shall be completed by the Metrology RO in conjunction with the RO for the system applicable providing information, as applicable, relating to the following requirements:

- First article inspection
- Goods inwards inspection
- Datum references and setting out
- Pre-alignment (fiducial measurement)
- Final alignment
- Data processing

- As-built measurements
- Measurement simulation

12.2 Design reviews

Alignment and metrology requirements and processes will typically be reviewed at the design reviews for the system to which they apply. Design reviews will be carried out in accordance with ITER Design Review Procedure (2832CF) current at the time.

The conceptual design review shall demonstrate that the alignment requirements and tolerances for the system under review have been identified and included in the Design Compliance Matrix (DCM). Specific details shall be included in the interface sheet of the appropriate interface control document as they are developed and must be in place before the final design review.

At the preliminary design review the outline processes for alignment should be presented to provide an overview of the scope of the task including an indicative schedule. At this time it should be clear where responsibilities lie for the various stages of the installation be it with the IO the DA(s) or as a combined effort.

Alignment and Metrology activities could include:

- Goods inwards dimensional inspection of system components
- Fiducialisation of components for assembly (section 11.9)
- Provision of reference datums, network points, elevation lines (section 8.0)
- Setting out for enabling activities: marking out for location systems, stillages etc.
- As-built reconstruction for customisation of interfaces
- Alignment of components: position, orientation, elevation….

Following the preliminary design review the alignment and metrology processes will be elaborated by the responsible officer(s) concerned. The level of elaboration will be dependent on a number of contributors such as the uniqueness of the task, the complexity of the process, access restrictions, required accuracy etc. The preliminary design review will define the scope of this elaboration which will subsequently identify the metrology input for the final design review.

The final design review shall demonstrate that dimensional control and alignment processes have been sufficiently addressed to ensure that the system under review can be successfully manufactured and subsequently installed at the ITER site. The Metrology RO will use the metrology handbook as reference for the review process and the DCM to assess compliance with the design requirements, contributing to the overall acceptance process.

13 QA and documentation

All components, processes, documents and data within the scope of this handbook shall be subject to the ITER Quality Assurance Program (IDM Ref; ITER_D_22K4QX) and its related Management and Quality Programme (MQP) (IDM Ref; ITER_D_2NS3UH).