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# MAGNETIC CLEANLINESS VERIFICATION APPROACH ON TETHERED SATELLITE

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## ABSTRACT

Magnetic cleanliness testing has been successfully performed on the Tethered Satellite as the last step of an articulated verification campaign aimed at demonstrating the capability of the satellite to support its TEMAG (TEthered MAgnetometer) experiment. Tests at unit level and analytical predictions/correlations using a dedicated mathematical model (GANEW programme) are also part of the verification activities. Details of the tests are presented, and the results of the verification are described together with recommendations for later programmes.

## INTRODUCTION

Nowadays the complexity of earth magnetosphere and ionosphere research by satellites is increasing; in this sense new and more advanced and innovative reseach methods are necessary. An opportunity for improvement in the knowledge of the Earth Magnetic Field at Low Earth Orbit altitude is provided by the Tethered Satellite System (TSS).

It is a joint project between the Italian Space Agency (ASI) and the United Sates National Aeronautics and Space Administration (NASA). Its goal is to test the feasibility of deploying, controlling and retrieving a Tethered Satellite from the Space Shuttle, as well as to demonstrate the system's usefulness for scientific research.

The TSS consists of an instrumented satellite, a thin, flexible tether up to 100 km long, a deployer attached to an enhanced Spacelab pallet in the Shuttle cargo bay, and scientific experiments on the satellite as well as in the cargo bay.

The Aeritalia Space Systems Group is the Italian prime contractor for TSS, responsible for the satellite. Martin Marietta - Denver Aerospace (MMA) is the American prime contractor responsible for the deployer and furnishing the tether. NASA is providing the pallet and an experiment carrier for the cargo bay. Both NASA and ASI will provide the science payloads being developed by selected experimenters.

The tether and satellite will be deployed from the Space Shuttle while it remains in orbit at an altitude between 230 and 300 km. In the first TSS mission, scheduled for the second half of 1991, the satellite and an electrically conductive tether 20 km long will be deployed above the Shuttle (spaceward) to study the electrodynamic magnetic fields and plasma properties.

The first TSS Mission is shown in Fig. 1.

In particular, this mission will test the feasibility of generating electricity with the tether as it cuts through the Earth's magnetic field. This could demonstrate a new source of auxiliary power for future spacecraft and space stations.

During the second TSS mission, anticipated to follow about two years after, the satellite will be deployed on a 100 km tether below the Shuttle (Earthward). In this configuration it will be possible to lower the satellite as far down as 130 km above Earth to reach a region of the atmosphere that previously could only be studied for brief periods by sounding rockets.

The TEthered MAGnetometer (TEMAG) payload is the experiment dedicated to the magnetic exploration of the TSS-S flight mission environment, on a well-known satellite magnetic status base; in this sense a Magnetic Cleanliness programme, to acquire knowledge of the magnetic properties of the satellite seen as a multipole, was necessary. In particular, a Magnetic Cleanliness verification campaign, comprising unique analysis and test steps has been performed at both unit and system levels.

The paper presents the Tethered Satellite characteristics and related magnetic cleanliness requirements, for the proposed combined verification approach and the test methods/facilities/results at equipment and system level. Suitable conclusions and recommendations for the next programmes are also included.

## TETHERED SATELLITE

## CONFIGURATION

The TSS-1 Satellite (TSS-S) is a retrievable vehicle, capable of carrying and supporting various scientific payloads simultaneously, up to 20 km away from the Orbiter.
The main characteristics of the TSS-1 satellite are:

* Current mass 518 kg and Diameter 1.6 m
* Spin-up/spin-down capability from 0 to ± 1.0 RPM (Present baseline is ± 0.7 RPM)
* Electrical connection between P/L and Tether, skin treated to allow current flow
* Telemetry Rate 16 kbps and Command Rate 2 kbps.

Fig. 2 shows the TSS satellite during integration activities at Aeritalia. Details on Tethered Satellite characteristics and operations can be found in Ref's 1 and 2.

The capacity of the TSS-1 is provided by a carrier approach and a modular concept of the Satellite configuration which comprises: an auxiliary propulsion module, a service module and a payload module.

### Propulsion Module

The propulsion module has one subsystem, the auxiliary propulsion subsystem (APS) which includes the GN2 tank, the in-line, in-plane, out of plane and yaw control thrusters, piping and valves to allow yaw attitude, yaw spin and Satellite translational position control.
All the APS parts except for the in-line thrusters are located on the equatorial floor. The APS is a cold gas (nitrogen) propulsion system so as not to contaminate the sensitive payload or the satellite external environment.

### Service Module

The service module includes the following subsystems.

- **Structure and Mechanism Subsystem (SMS)** - The basic concept and the main components of the TSS satellite structure are shown in Figure 3.
  The satellite has two fixed booms, for mounting the S-band antenna and science instrumentation respectively and two deployable/retrievable booms carrying science instrumentation.
  Four access doors are provided for battery installation at KSC in the Orbiter bay in the vertical position. The tether attachment is the mechanism provided to allow mechanical and electrical tether connection to the satellite.

- **Electrical Power and Distribution Subsystem (EPDS)** - The internal power source of the TSS-S is a battery system, consisting of four silver-zinc (Ag-Zn) batteries, arranged in series/parallel.
  A power command distribution assembly (PCDA) basically performs the distribution of the power to the subsystems and the conditioning of some commands dedicated to the activation of relays and valves.
  The payload power distribution assembly (PPDA) is a distribution unit dedicated to the payload and is in the payload module.

- **Harness Subsystem (HRNS)** - The HRNS provides electrical interconnections for the distribution of the electrical power and signals between all satellite units, units to EGSE skin connector, and units to umbilical connectors.

- **On-Board Data Handling Subsystem (OBDH)** - The OBDH S/S consists of the following units: Central Terminal Unit (2 microprocessors - 1 dedicated to AMCS processing), Memory Bank Unit, Remote Terminal Unit Service, Remote Terminal Unit Payload (mounted within payload module), Decoder and OBDH Busses.
  The OBDH is immediately powered as soon as the PCDA receives power from the batteries or from the TSS-Deployer.
  Upon power-up, the OBDH will automatically perform a self check providing the results in the TLM page and then the software programs to support the mission will resume. In addition, the OBDH will be ready to execute/distribute commands coming from the umbilical hardline sent through Radio Frequency (RF) link.

- **Attitude Measurement and Control Subsystem (AMCS)** - The AMCS determines the TSS-S attitude and provides telemetry on Satellite vector yaw, pitch and roll measurements. The AMCS controls the yaw attitude and the TSS-S spin rate. The AMCS processor is part of the OBDH subsystem. The AMCS includes the TSS-S gyroscope package, sun sensor package and earth sensor package.

- **Telemetry and Telecommand Subsystem (TT&C)** - The TT&C provides the S-band link between the satellite and orbiter when the TSS-S is in the detached mode.
  TT&C functions include telecommand/data reception, telemetry data transmission, and subsystem housekeeping. It consists of the S-band antenna, S-band transponder and RF cable.

- **Thermal Control Subsystem (TCS)** - In order to guarantee a suitable thermal environment for the satellite, the TCS makes use of the following components/materials: paints on external skin, Multi-layer Insulation blankets on equipment, fillers, heaters and thermostats for heater control.

- **Engineering Instrumentation Subsystem (EIS)** - In order to verify that the satellite thermal environment remains within the allowed limits during the mission phases, the EIS provides monitoring by means of redundant thermal switches and sensors.

Figure 4 shows a TSS-S synthetic block diagram showing the interfaces with Deployer, Orbiter and Payloads.

### Payload Module

The payload module provides accommodation for the four scientific payloads. Experiments/sensors are located inside the payload module, on the external Satellite skin, on an external dedicated fixed boom and on the Deployable Retrievable Booms. The payloads on the Satellite for TSS-1 are:

- Magnetic field experiment for the TSS missions (TEMAG) by University of Rome
- Research on Electrodynamic Tether Effects (RETE) by Institute Fisica Spazio Interplanetario, CNR
- Research on Orbital Plasma - Electrodynamics (ROPE) by Space Science Laboratories, MSFC
- Satellite Core Equipment (SCORE) by Aeritalia

In particular the TEMAG Experiment consists of the two magnetometers and their electronic package.
Each FluxGate Magnetometer (FGM) unit contains three monoaxial fluxgate sensors in a mutually orthogonal array measuring the vector magnetic field in the frequency band from DC to 8 Hz. One unit (FGM/O) will be mounted at the tip of the Satellite fixed boom and the other (FGM/I) on the same boom close to the Satellite (see Fig. 2).

## VERIFICATION AND TEST PROGRAMME

On the basis of the programme's industrial architecture, the overall design and performance requirements relevant to the TSS-Satellite are contained within a set of dedicated specifications and Interface Requirement/Control documents.

The levels through which verification of the above Tethered requirements has been performed incrementally are: system, satellite, payload, subsystem, unit. The verification methods established for the TSS are: Similarity, Analysis, Demonstration, Validation of Records/Design, Test.

The test effectiveness is for qualification of acceptance; development tests are not considered valid for formal verification close-out.
The definition of the applicable verification methods for each satellite requirement originated a coherent model philosophy as summarised in Fig. 5.

The correspondent system Integration and Test Programme foresees: a Structural Model on which a complete structural qualification test campaign (i.e. Physical Properties, Model Survey, Acoustic, Alignment and Leak tests) has been carried out at IABG's laboratories in Munich; an Engineering Model on which a functional test campaign (i.e. Magnetic Cleanliness Measurements, Service Module Test, Payload Module Test and Satellite Integrated Test) has been performed in Aeritalia; a Flight Model, subjected to functional and environmental acceptance tests (i.e. Functional, EMC, Physical Properties, Alignment, Thermal Vacuum/Balance, Acoustic, Leak and Magnetic Cleanliness Test) at the IABG facilities.

Ref. 3 contains details of the TSS Satellite Integration and Verification philosophy.

## MAGNETIC CLEANLINESS VERIFICATION

### Requirements and Verification Approach

Magnetic cleanliness requirements have been specified on TSS-S with the objective to know and possibly limit the magnetic contamination of the TEMAG experiment measurements due to the satellite magnetic field.

In fact, the satellite background has to be subtracted from the experiment measurements, performed at LEO altitude, in order to get reliable data of TEMAG magnetic exploration. The level of "cleanliness" for the satellite magnetic environment has been specified as a design goal in terms of 20nt at FGM/O location, associated with an acceptable degree of magnetic stability ( ± 1nt).

The verification of the satellite compatibility to the above requirements and the associated evaluation of its magnetic emission and susceptibility was performed using a combined analysis/test verification approach as shown in Fig. 6.

In particular the approach used develops test activities at both unit and satellite levels associated with iterative analysis campaigns worked out by means of a suitable software programme.

The system analytical model has been developed by using test results of the majority of the satellite units and has been used to predict the system test results. Final validation of the system model, including the contribution of the parts not tested at unit level (for example the structure), has been performed correlating the system test results.

In addition, the chosen incremental verification approach allowed a better control of the TSS-S Flight Unit magnetic cleanliness because the verification campaign at unit level provided early evidence of difficulties in meeting the system cleanliness requirement and suggested useful recommendations for system design and test.

### Model and Analysis

The tool used to perform the magnetic cleanliness analysis is an ESA programme called GANEW (see Ref. 4). It is based on a multiple dipolar modelling of the test object; this method is derived from the postulate that a given magnetic field configuration around a test object can be represented adequately by a finite set of discrete dipoles within the test object at a distance where the multipolar field components can be neglected. Unfortunately, the problem is in general conditioned in the sense that a unique solution identical with the real source involved does not necessarily exist; nevertheless, in some particular cases the approximation to have a dipole model can provide useful information about the real source.

A very effective optimisation procedure of the Gauss-Newton type is used in the programme to determine the dipole positions and moments of the model which reconstitute the magnetic field measurements.

The GANEW programme is associated with a suitable test procedure in the sense that, on the basis of unit test data results, it is able to calculate the magnetic field contribution individually of each unit, and totally of the complete satellite at specified points - for instance FGM/O location for TSS-1.

An important parameter in dipole modelling is the distance between the test object and the measurement probe which has a direct influence on the magnetic field momentum value. In this sense the GANEW programme is used to perform iterative analysis to optimise the test set-up and provide good estimation of the measurement errors.

This shall be possible, before starting with a test, comparing a set of field data generated by a well known magnet (position and moment) in the test object measurement position w.r.t. the probe data results of the coil facility used. After the set-up optimisation process, the results of the measurement performed on the test object rotating around a 360 degree coil turntable plane, elaborating the drift effects by computer, provided already formatted input data for the GANEW programme (see typical data for TSS in Fig. 7)

The programme operates with the above input of rotational measurement to calculate a best fit dipole as unit dipole model in unit coordinates which contributes to the S/L modelling by vectorial superposition of the unit models in S/L coordinates, finally to produce the Synthetic Satellite Model (see TSS example in Fig. 8).

Once a representative and minimum dipole model in the Form of the number of dipoles, their position coordinates and their moment vectors have been found, the S/L model can be used to calculate the magnetostatic field configuration around the test object at virtually any point but no closer to the test object than the nearest measurement point. This is possible by means of the direct mathematical summation of the moments.

By using the established analytical model, it is therefore possible to predict the relevant individual field at FGM/O location provided by one single unit, and the integrated field originated unit by unit (see Fig. 9 for TSS FU Perm phase) for each system test phases of a unit magnetic characterisation. Typical representation of the GANEW programme elaboration using the synthetic Satellite Model for TSS is sketched in Fig. 10 (plane representation) and in Fig. 11 (tridimensional representation). At the end of the system test activities, the analytical model is validated by comparing analysis results with respect to the test results; the final picture of the model represents the satellite configuration to be used for in-flight data evaluation.

### Test at Unit Level

Dedicated Magnetic Cleanliness tests have been performed on TSS-S FU units as part of the overall verification campaign, with the objective to provide inputs for the satellite model definition for the following interested conditions: 50 GAUSS Deperm state, 5 GAUSS Perm state and Stray field contribution in the power-on state.

As part of the cleanliness control programme, rules for the design of magnetically clean hardware were established and advice given to TSS-S experimenters and all unit subcontrators. The unit level test campaign has been carried out in AERITALIA Space Systems Group's Integration area in Turin using a mobile coil facility, provided by Technical University of Braunshweig, in which about 41 boxes were automatically mapped through the following test phases (see Ref. 5 for details):

- Initial state
- Initial Deperm 50 GAUSS
- Perm 5 GAUSS
- Final Deperm

Measurements were performed on each box axis on a rotating non-magnetic platform, at the centre of the mobile coil facility, in which a compensating earth magnetic field down to about 0.1 nt is provided by using 2 vertical and 2 horizontal compensation coils.

To Perm/Deperm the unit placed at the centre of the facility as shown in Fig. 12, another 2 lateral Perm/Deperm coils were used, and for measurement a 3-axial-probe was positioned to originate an orthogonal axes reference system on one side of the test object. The probe x-axis pointed towards the centre of the turntable and the z-axis in the direction of the turntable rotation axis (see Fig. 13).

Measurements were taken with the test object turned over 360 degrees by a manual angular resolver of the turntable, and automatically taken in steps of 10 degrees for a total of 36 measurements for each test phase at the end of magnetic field application (Fig. 7 shows the results).

To evaluate stray field contribution due to electric current, the box was powered and measurement taken after performance of the Deperm field, with the unit in OFF and in ON condition.

Quite an important parameter for testing is, of course, the distance between probes and test object; the distance must be chosen reasonably in such a way that a field is mapped approximately on a sphere around the test object, and optimised by means of a calibration magnet before starting the tests.

For correct test results, evaluation was also necessary to specify and provide box Center of Gravity (CoG) geometry w.r.t. the Unit Coordinates System (unit reference hole); the box reference hole geometry relative to Satellite Coordinate System (SCS) and the CoG geometry relative to the centre of the turntable (UCS), as input data for the GANEW programme.

It was important to know the position of each single unit within the Satellite reference system because it was necessary to allocate the magnetic dipole moment representative of the unit, to these positions, to define finally the model of the S/L's global moment. The early verification at unit level was also useful to point out, before the system test, some criticalities, especially for DRBD/A FU experiments.

In fact, interest focussed on the cleanliness investigations of these last items of the model detected that a simple Deperm at Boom stowed, as foreseen during unit level characterisation, was not efficacious, but it was mandatory to effect a dedicated local degaussing to estinguish some hot spots present on accessible Boom parts in Deployed configuration only. In this way it was possible to reduce the otherwise compromised DRBD/A residual magnetic field to the required value.

This was a classic example of positive iteration that made it possible for the system test to evaluate the corrective solution to the problem; in fact an additional dedicated local degaussing of the DRBD/A Boom in deployed configuration was required at the final stage to guarantee the minimum value of residual field to reduce the S/L magnetic emission at FGM/O location.

Therefore, despite incomplete cleanliness (i.e. because of size limitation it was not possible to test structure, APM and Harness) during S/L integration, the results shown in Fig. 8 and in Fig. 9 have been of extreme importance for the overall cleanliness verification. The TSS-S magnetic cleanliness programme performed at unit level can be considered fully accomplished at this point.

**Test at System Level**

On completion of the overall TSS-S FU cleanliness verification campaign, the magnetic cleanliness test at system level was carried out at the IABG MSFA II coil facility in Munich-Ottobrunn. The test has been developed with the objectives to simulate the S/L in orbit as much as possible to obtain reliable characterisation of the TSS-S FU magnetic behaviour in space flight condition.

A testing of Satellite magnetic emission and susceptibility was mandatory with a complete marking of this influence on the space magnetic environment to be explored by the TEMAG experiment; this is to realise a defined requirements verification on a test method base in terms of: compatibility to the TEMAG environment, and validation of the system analytical model by correlation with the system test results.

The main test objectives pursued during system test were:

* S/L characterisation of emissivity as received
* S/L Deperm measurement and Stray field contribution in the power-on state
* S/L characterisation of susceptibility as Perm state
* S/L characterisation for Induced Fields and Eddy Current effects

The system test was performed within IABG's special Magnetic test facility (Fig. 14) with the satellite installed on a rotating "column" of non-magnetic adaptors positioned at the centre of the coil system, with the S/L x axis aligned with the Probes facility x axis, (measurement position).

During the test, a value of 20NT at FGM/O location was continuously monitored by 4 probes in the vicinity of two FGMO/I and together with a set of strip-charter analog recorders.

Four 3-axial fluxgate magnetometers were used for rotational measurement: complete 360 degrees around S/L z axis for 36 intervals of 10 degrees each one (partial mapping), and ± 20 degrees around S/L z axis for 10 intervals of 5 degrees each one (partial mapping), except the last one which equals the starting measurement (-20 degrees), w.r.t. the S/L measurement position.

The 4 MFSA probes were placed near the FGMO/I magnetometers, 2 vertically (5 cm up and 10 cm down from FGM/I) and 2 horizontally as near as possible to the FGM/O x plane, see Fig. 15.

The test objective has been reached through the following test conditions:

- **Initial State** - The complete 360 degree mapping in 10 degree steps of the S/L as received gives the most important status result of the magnetic behaviour of the TSS-S because, being moved to the ground field environment after the test, it could be permed up as it will be during launch.

- **Deperm state** - The residual magnetic state of the satellite is tested after demagnetisation provided by the facility's Perm/Deperm coils to get evidence of the stray magnetic field, to be kept to the minimum possible.
  It should be noted that the same values could not be achieved in the different Deperm states because of physical disorientation imparted to the magnetic parts. Magnetic effects could be increased, however, without risking stability.

- **Perm state** - The Perm shows the susceptibility of the Satellite to external fields, like earth field (0.5 Oe), structures, cranes, trucks, and launchers, which may show fields up to 1.5 Oe. Only S/L x axis was detected particularly susceptible to Perm Field. See Run 12 Fig. 17.

- **Stray** - This is the only test which shows the Satellite in power-on condition. Each S/L unit will be switched on, one after the other in the most powerful mode while TEMAG is watching. This is the only test to look for current loops throughout the Satellite as well as possible grounding problems and interference by currents in the structure.
  The stray field test has been performed actuating equipment critical from a magnetic emission point of new as DRBD/A boom motor and APS valves.
  The contribution by test estimated at FGM/O location for stray field effects is about 1.7 nt as calculated with linear interpolation of data. Linear interpolation is the worst case in an approximation law representative of the S/L magnetic field distribution in relation to the distance. In reality the S/L field distribution is representated by a hyperbole law on a ratio 1 of 3, and hence the obtained results by modelling are better than with linear interpolation.

- **Temag Calibration and Induced Fields** - Because the satellite contains soft and hard magnetic material, the ambient field (which should be measured) will be deflected if the satellite is moved into the field. Therefore the Magnetometers measurement will show a combination of ambient field and azimuth dependent inductions.
  This characterisation was also performed during system tests.

- **Eddy Currents** - Any conductive rotating or moving in an ambient field will cause eddy current and these will produce a magnetic field. So any conductive skin shield should be made as thin as possible and be of high resistance.
  All conducting structural loops should be avoided. For this purpose, the test at system level has been conducted suspending the S/L with nylon ropes and with two facility magnetometers in differential mode set-up, to detect eddy current originated by S/L effect during a rotating magnetic fields application.

- **Final Deperm** - Final 50 Gauss Deperm field is mostly performed to get a Satellite as clean as possible ready for launch.
  Because the TSS-S FU will be moved, transported or stored in the earth field or in possible stronger field environments, this test would not be representative if a dedicate magnetic cleanliness control campaign is not conducted to ensure the required environment of no more than 1.5 Gauss of magnetic field.

On the basis of the above test objectives and conditions the following sequence was executed during the S/L magnetic cleanliness test (see Ref. 6 for details):

* facility calibration (well-known magnet used)
* S/L as received measurement (partial mapping/mapping - RUN's 3 and 2)
* DRBD/A deployment
* S/L sniff test and DRBD/A local degaussing
* DRBD/A retrieval
* Initial S/L measurement (partial mapping/mapping - RUN 7)
* First deperm
* First deperm measurement (partial mapping/mapping - RUN's 6 and 7)
* TEMAG calibration
* Induced field
* Perm S/L on each single X,Y,Z axes at four different levels of Perm field - 1,2,3,5 Gauss - executing at the end of each field application a sniffing of the fixed Boom and a partial mapping. Mapping measurement was only performed for the last 5 Gauss Perm field applications at S/L Z axis (RUN's from 8 to 21).
* Second deperm 50 Gauss
* Measurement (partial mapping/mapping - RUN's 23 and 22)
* Stray field (measurement on S/L fixed position - RUN's 24)
* Final deperm
* Measurement (partial mapping/mapping - RUN's 26 and 27)
* Eddy current

Sniff tests are included in most test phases to guarantee that the level of residual magnetic field is not disturbed by local sources of magnetism (hot spot) that often were the most frequent causes of an increase in the S/L magnetic contribution at FGM/O location. For example the field has been significantly reduced (see RUN's 4 and 7 of Fig. 17) by local degaussing of some hot spot presence on the ROPE experiment, positioned below the S/L FGM/O unit.

It is pointed out that to detect the hot spot a dedicated sniff test is needed, otherwise the usual rotational measurement is not able to locate these local sources.

To get the best value resolution of the 20 nT verification, a range measurement has been adopted about each 5 degree around ± 20 degree w.r.t. the Satellite measurement position. These data have been approximated to worst case requirement evaluation by means of a linear interpolation of the two probes data closed to FGM/O.

The local degaussing activity on DRBD/A boom, for hot spot extinguishing at boom deployed, decreased the value of magnetic field from 32.5 nT to 27.1 nT (RUN's 3 and 6 of Fig. 17)

From data observation of partial mapping measurement and mapping measurement of the same test phase, it is possible to have an idea of how real the modelling elaboration is w.r.t. to the linear interpolation of the facility probe data results. GANEW modelling elaboration and the facility test evaluation have revealed differences of about 2.5 nT (see RUN's 4/7/29 of Fig. 17. This 10% of difference between model and test results gives positive answer to the validation of GANEW mathematical model.

With regard to the testing environment, the design goal of 20 nT has been acceptably approximed (25.9 nT, see Fig. 18) with a good degree of S/L magnetic field stability, only 1 Gauss of difference between the 1st and 3th deperm, which is fundamental for the offset value to be subtracted from TEMAG reading performed in flight condition.

The complete Magnetic Cleanliness campaign on TSS-S FU could be considered successfully performed at this level. To preserve the Satellite Magnetic status until the launch date, only a detailed activity with interest of magnetic cleanliness control is required, i.e. not to expose the TSS-S FU to a field exceeding 1.5 Gauss.

## CONCLUSIONS

The Tethered Satellite Magnetic Cleanliness Verification Campaign has been successfully carried out through a series of test activities at unit and satellite levels involving unique test set-ups and facilities. Those activities have been combined with analytical evaluation using a specific programme which originated a magnetic model able to support TEMAG flight measurements.

The Experience gained on Tethered Satellite supports possible improvements for future projects; the major recommendations are:

- the verification campaign should be helped by a more stringent magnetic cleanliness control in terms of design verification and magnetic cleanliness follow-on during manufacturing and integration
- a complete test campaign at unit level, including all the satellite parts as much as possible, is fundamental for early critical point discovery and fixing
- increasing sniff test executions during test at unit level will improve the knowledge of S/L hardware magnetic properties that is of extreme importance for implementation of the Magnetic Cleanliness control campaign
- an increasing of perm magnetic field on satellite level to values up to 10 Gauss should offer a suitable margin for the susceptibility verification not only for the flight environment but also for the ground environment
- final system test could not be recommended if the Satellite is not ready for launching after testing, but has to be moved, transported or stored to earth field or a stronger field environment. In this case the final deperm should be postponed.

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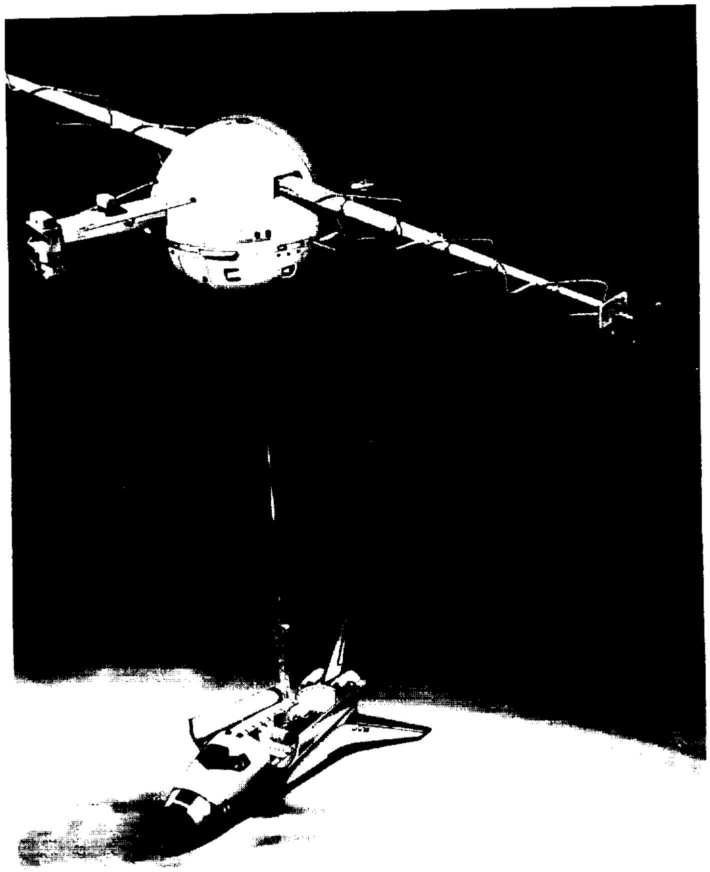

**Fig. 1 - Tethered First Mission**

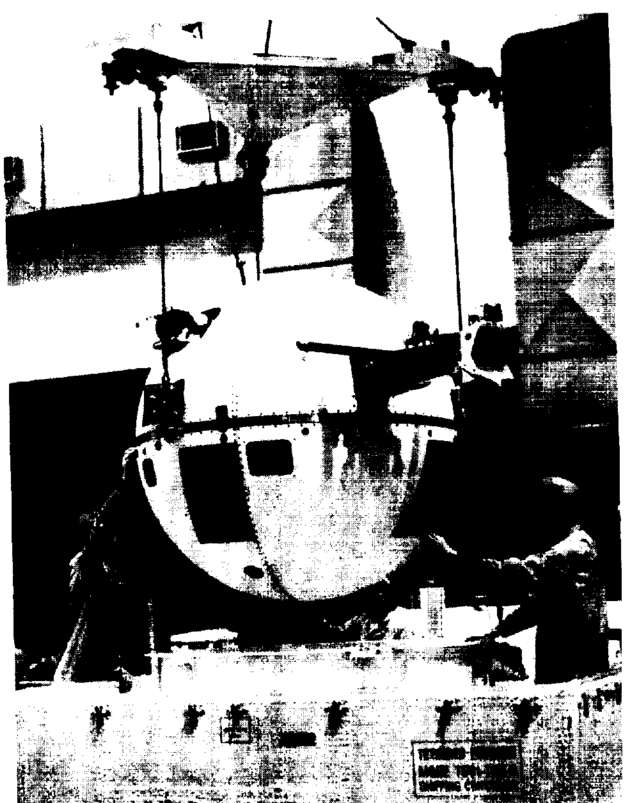

**Fig. 2 - TSS Satellite**

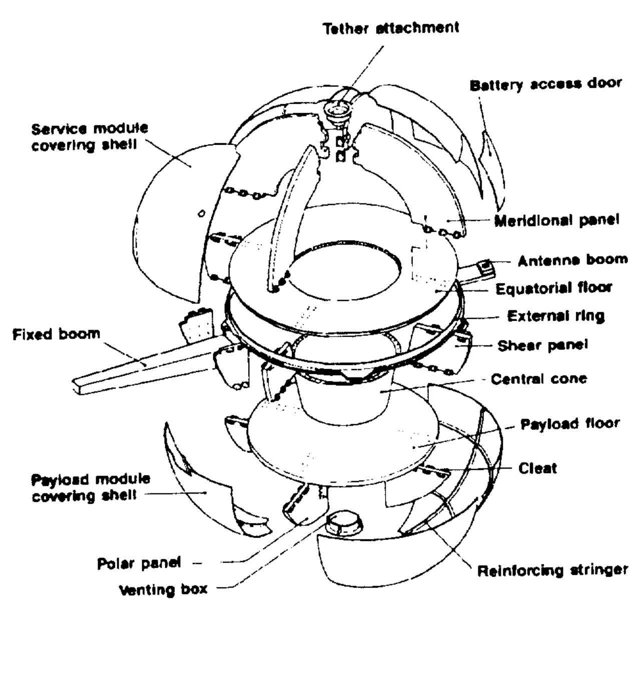


**Fig. 3 - TSS-S Structural Exploded View**

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ORIGINAL PAGE IS
OF POOR QUALITY

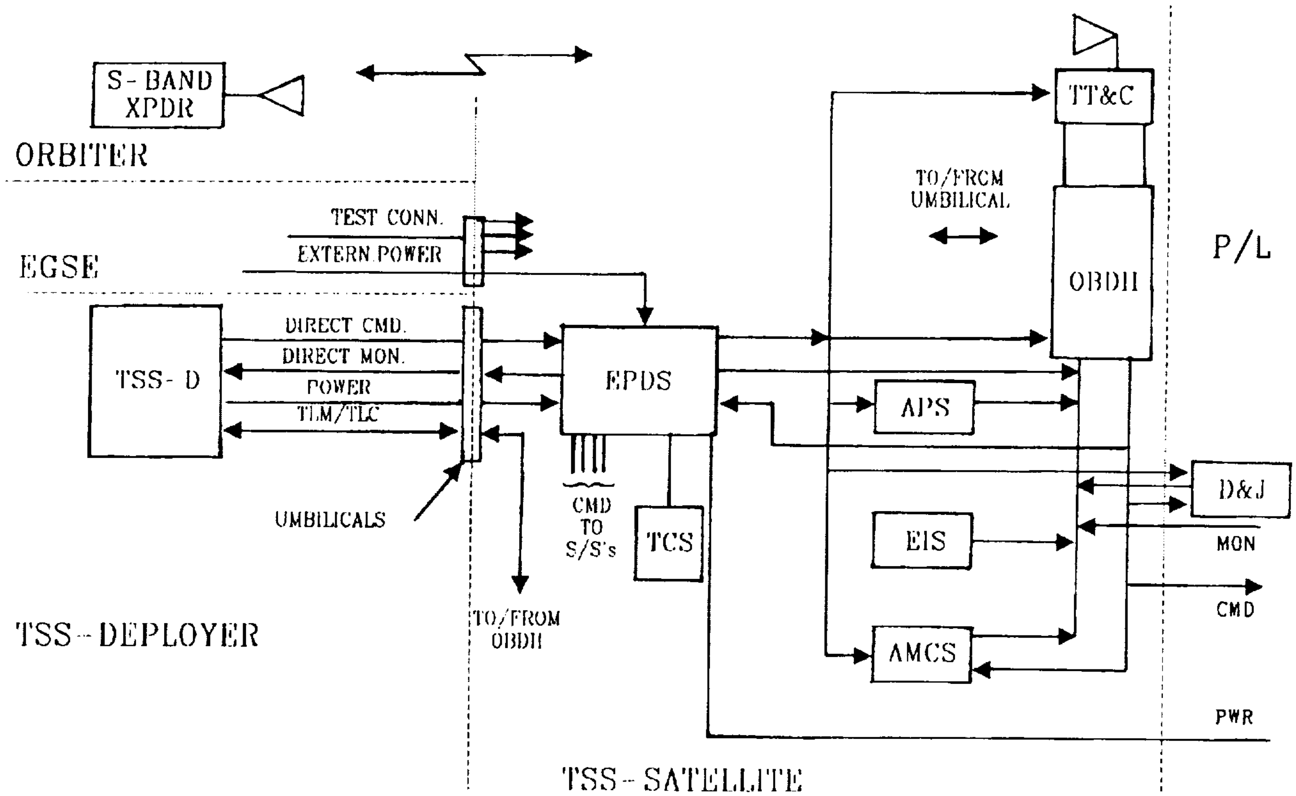


**Fig. 4 - TSS-S Functional Block Diagram**

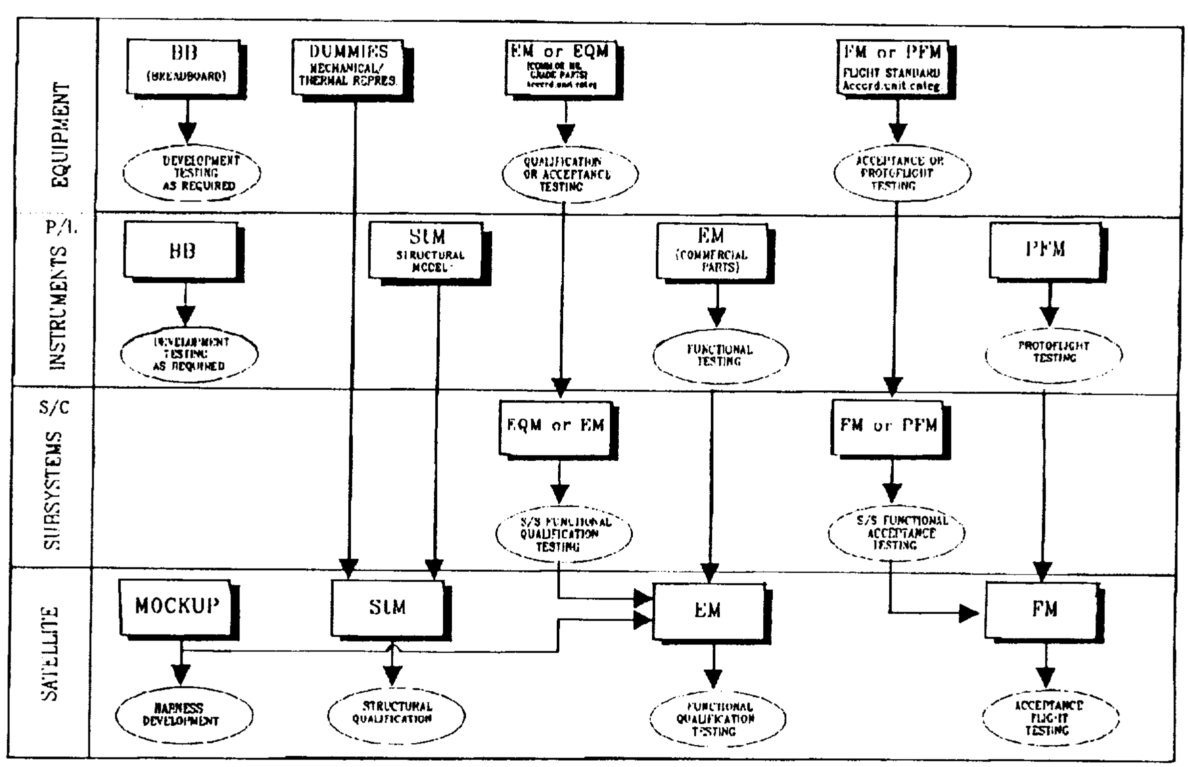


**Fig. 5 - TSS-S Model Philosophy**

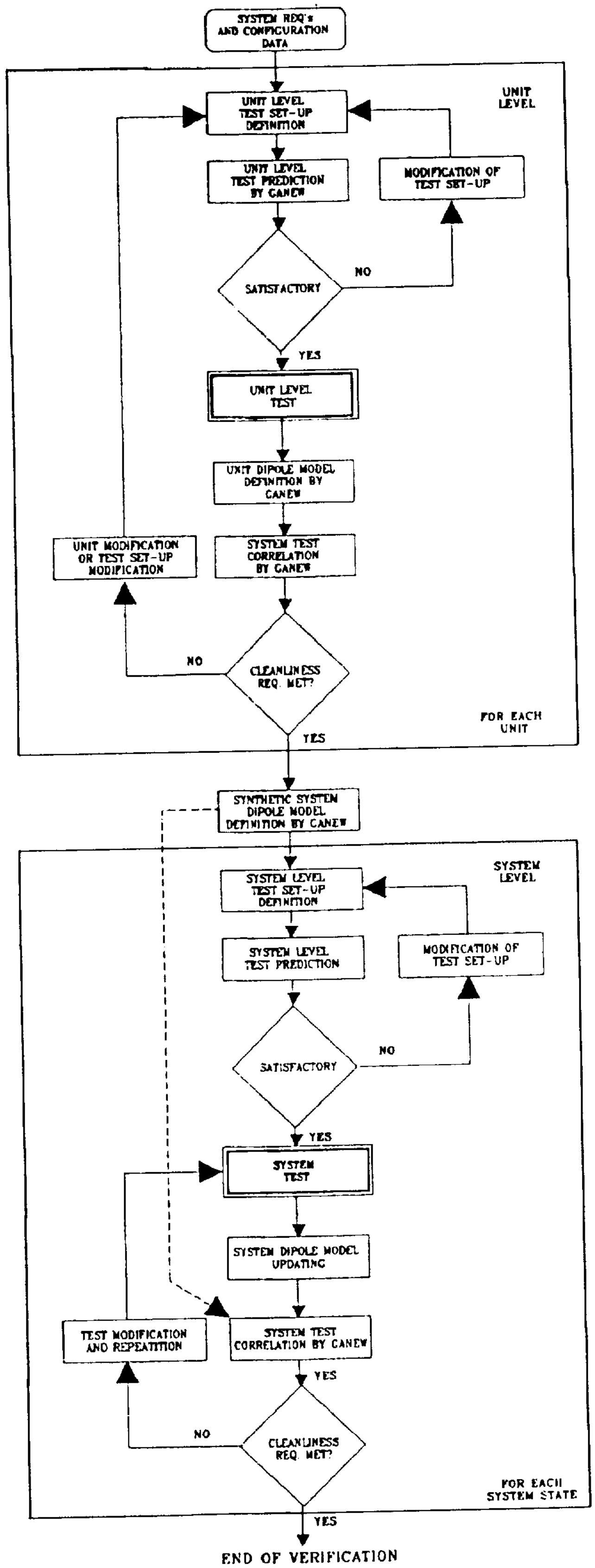


**Fig. 6 Magnetic Cleanliness Verification Flow**

AER-TURIN 03/11/89 14:54:48
FUDEC
Test No.: 5 PERM
Rotation increment: 10 deg. 37 data triplets

| PHI(deg.) | BX(nT) | BY(nT) | BZ(nT) |
|---|---|---|---|
| 0 | 10.8 | -6.3 | -1.1 |
| 10 | 16.0 | -11.7 | -4.0 |
| 20 | 14.2 | -10.5 | -1.4 |
| 30 | 0.9 | -6.9 | 0.0 |
| 40 | -3.7 | -4.0 | -1.8 |
| 50 | -6.9 | -3.4 | -3.4 |
| 60 | -4.3 | -2.0 | -5.6 |
| 70 | -17.7 | 3.5 | -13.6 |
| 80 | -12.8 | 4.9 | -22.4 |
| 90 | -12.5 | 5.3 | -22.4 |
| 100 | 0.5 | 1.5 | -7.0 |
| 110 | -1.5 | 1.8 | -3.1 |
| 120 | 4.0 | -1.8 | -5.0 |
| 130 | 4.7 | -2.9 | -4.0 |
| 140 | 0.5 | -2.4 | -2.9 |
| 150 | -2.6 | -3.4 | -7.0 |
| 160 | 1.4 | -7.3 | -12.8 |
| 170 | -1.5 | -4.0 | -13.6 |
| 180 | 0.9 | -2.1 | -9.0 |
| 190 | 6.0 | -1.4 | -5.2 |
| 200 | 2.6 | 0.2 | -7.3 |
| 210 | 5.0 | -2.4 | -11.1 |
| 220 | 6.1 | -2.3 | -9.2 |
| 230 | -3.7 | 1.1 | -11.6 |
| 240 | 9.2 | 1.1 | -5.3 |
| 250 | -4.0 | 3.4 | -9.2 |
| 260 | 8.9 | 1.2 | -6.7 |
| 270 | -0.2 | 3.2 | -10.4 |
| 280 | 13.3 | 1.7 | -6.1 |
| 290 | 6.0 | 3.1 | -7.6 |
| 300 | 20.0 | -1.4 | -6.6 |
| 310 | 15.3 | -0.2 | -2.9 |
| 320 | 23.8 | -3.7 | -4.9 |
| 330 | 15.9 | -3.8 | -3.5 |
| 340 | 21.1 | -8.4 | -3.4 |
| 350 | 15.9 | -8.4 | -1.4 |
| 360 | 14.5 | -10.5 | -3.2 |

| | | | |
|---|---|---|---|
| DUT-DIM. (CM): | 24.90 | 22.60 | 11.20 |
| DUT-MASS (GR): | 2627.0 | | |
| DUTRH-S/C(CM): | -16.60 | 19.40 | -44.40 |
| DUT-ROT. S/C : | 0.65 | -0.65 | -0.38 |
| | -0.27 | 0.27 | -0.92 |
| | 0.71 | 0.71 | 0.00 |
| DUT-CG (CM): | 0.00 | 0.00 | 5.50 |
| DUT-RH (CM): | -6.90 | -10.30 | 0.00 |
| DUT-LIMIT(CM): | -12.6 12.3; | -11.1 11.5; | 0.0 11.2 |
| DUT-ROTATION : | 1.00 | 0.00 | 0.00 |
| | 0.00 | 1.00 | 0.00 |
| | 0.00 | 0.00 | 1.00 |
| SENS-CT (CM): | 35.00 | 0.00 | 0.00 |
| X-SENS. (CM): | 0.00 | 0.00 | 3.00 |
| Y-SENS. (CM): | 0.00 | 0.00 | 6.20 |
| Z-SENS. (CM): | 0.00 | 0.00 | 10.50 |
| OFFSET (NT): | 2.98 | -5.42 | -41.43 |
| RES-FIELD(NT): | -28.76 | 16.56 | 38.22 |
| O/NO DUT (NT): | 1834.72 | 46.84 | -524.14 |
| O-CHECK (NT): | 1843.11 | 46.69 | -530.55 |

**Fig. 7 - Rotational Inputs for GANEW**

MAGNETOSTATIC CLEANLINESS CONTROL CHART        Date: 130190

MSC41(FD)

Project : TSS-1

Model : FU

Magnetic Status: Final Deperm

Legend:

| | | | |
|---|---|---|---|
| rms | = | Field Measurement Reconstitution Error | (nT) |
| M | = | Global Dipole Moment | (Gcm3) |
| FGMI | = | Field at FGMI Location (-126.70 1.90 22.50 cm) | (nT) |
| FGMO | = | Field at FGMO Location (-177.80 1.90 20.00 cm) | (nT) |
| mod | = | Module of Vector | (nT) |
| 1 | = | x-Component of Vector (S/C Coordinates) | |
| 2 | = | y-Component of Vector (S/C Coordinates) | |
| 3 | = | z-Component of Vector (S/C Coordinates) | |

(Spacecraft fields are vector sums of unit fields)

| Unit | | | | | | | Spacecraft | | |
|---|---|---|---|---|---|---|---|---|---|
| | Unit | Run | rms | M | FGMI | FGMO | FGMI | FGMO | |
| 1 | FUPCDA FINAL DEPERM | 7 | 5. | 61.5 | 1.89 | 0.82 | 1.89 | 0.82 | mod |
| | | | | 9.5 | -1.65 | -0.54 | -1.65 | -0.54 | 1 |
| | | | | -38.8 | 0.44 | 0.35 | 0.44 | 0.35 | 2 |
| | | | | 46.8 | -0.82 | -0.51 | -0.82 | -0.51 | 3 |
| 2 | FUPPDA FINAL DEPERM | 5 | 4. | 72.1 | 4.29 | 1.80 | 2.65 | 1.32 | mod |
| | | | | 65.8 | 4.10 | 1.76 | 2.46 | 1.22 | 1 |
| | | | | -5.3 | -1.25 | -0.37 | -0.81 | -0.02 | 2 |
| | | | | 28.8 | 0.24 | 0.02 | -0.58 | -0.49 | 3 |
| 3 | FUWRA FINAL DEPERM | 7 | 3. | 7.7 | 0.13 | 0.06 | 2.67 | 1.31 | mod |
| | | | | 1.6 | 0.03 | 0.02 | 2.49 | 1.23 | 1 |
| | | | | 2.2 | -0.04 | -0.02 | -0.85 | -0.04 | 2 |
| | | | | -7.2 | 0.11 | 0.06 | -0.46 | -0.44 | 3 |
| 4 | FUDCE FINAL DEPERM | 12 | 3. | 12.8 | 0.75 | 0.31 | 2.40 | 1.21 | mod |
| | | | | -9.4 | -0.17 | -0.15 | 2.32 | 1.08 | 1 |
| | | | | -8.2 | 0.72 | 0.27 | -0.14 | 0.23 | 2 |
| | | | | 2.8 | -0.13 | -0.05 | -0.60 | -0.49 | 3 |

**Fig. 8 - Elaboration of Synthetic Satellite Model**

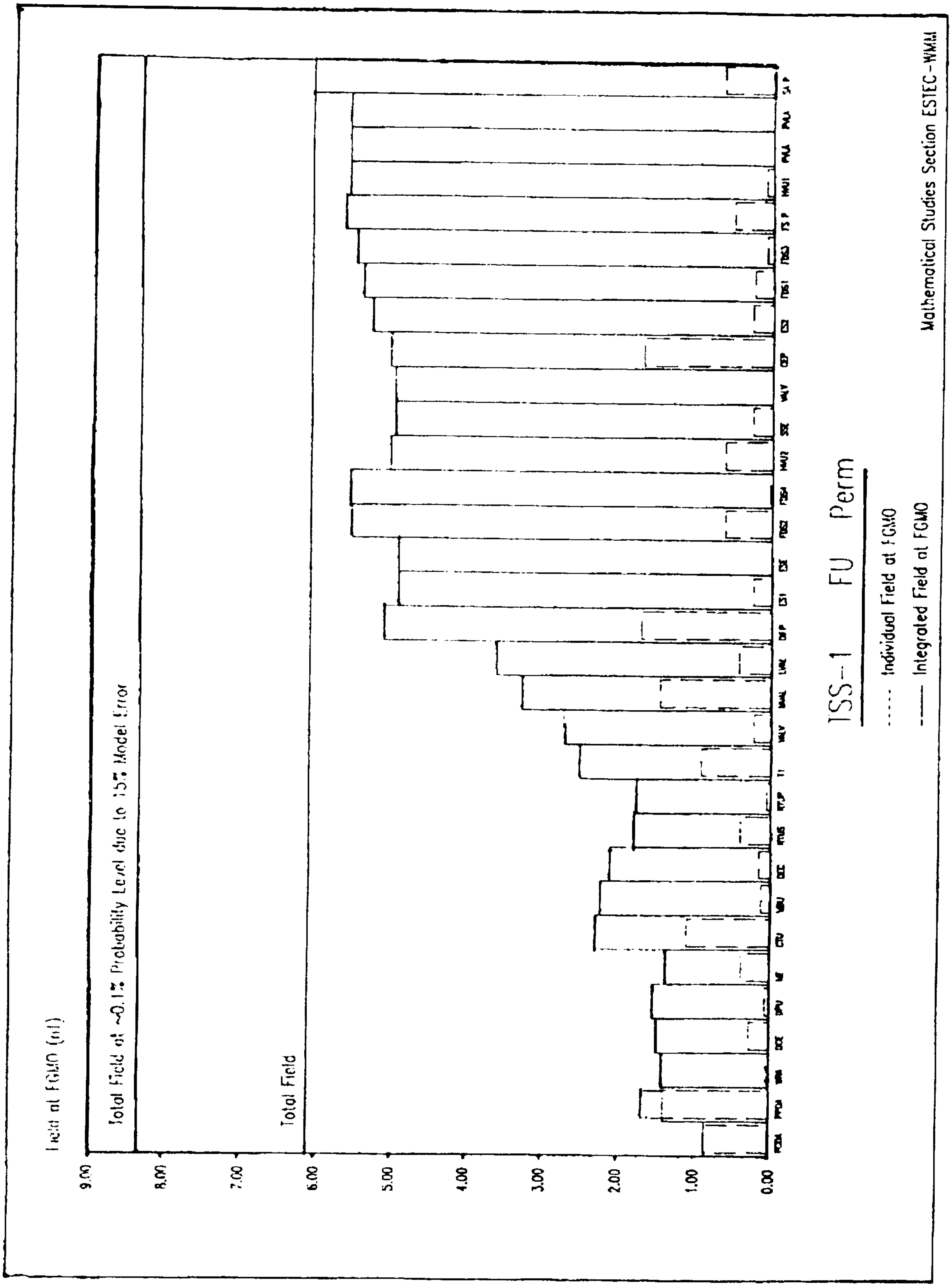


**Fig. 9 - TSS-S Perm Phase Magnetic Field Contribution**

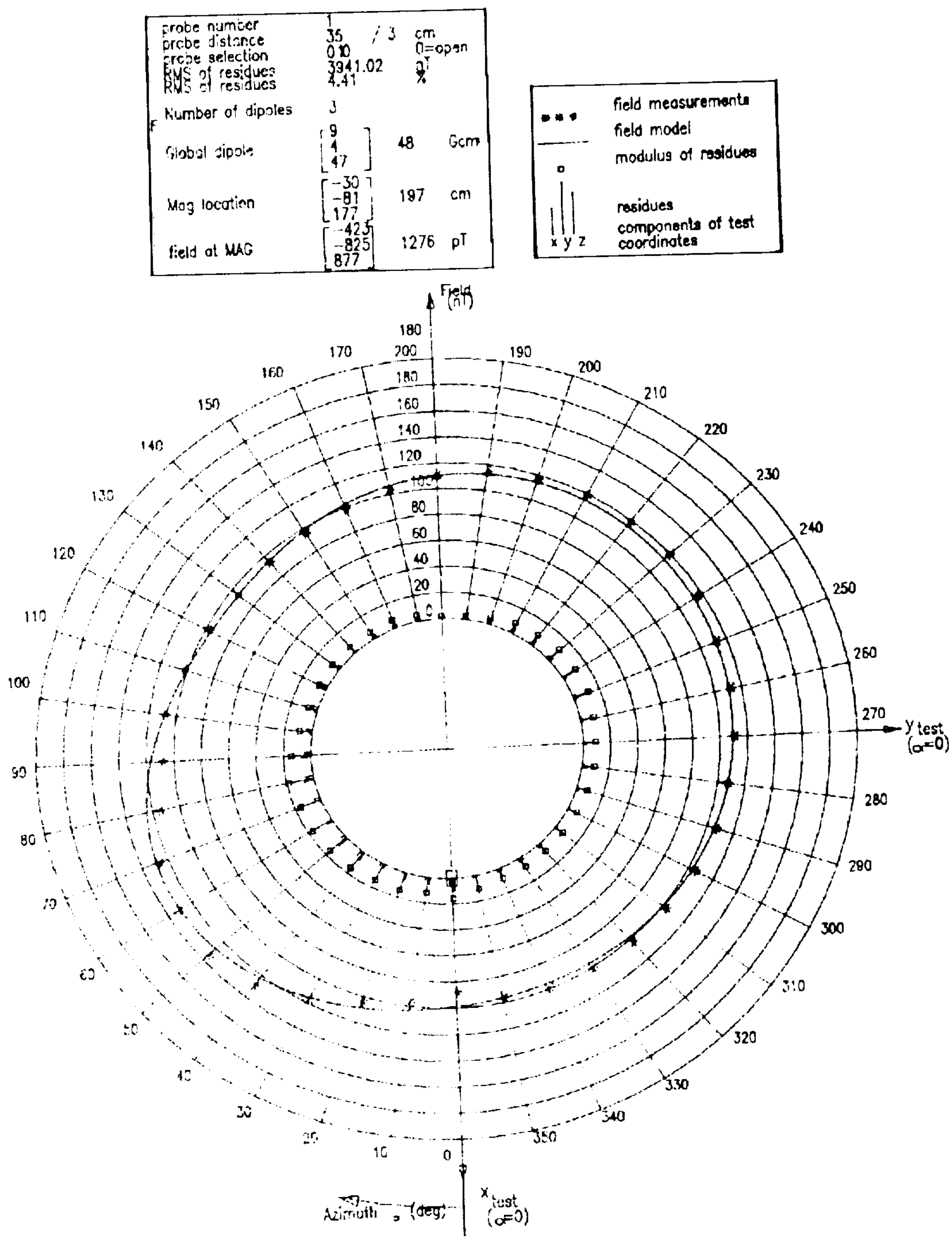


Fig. 10 - GANEW Synthetic Satellite Model Output (Plane)



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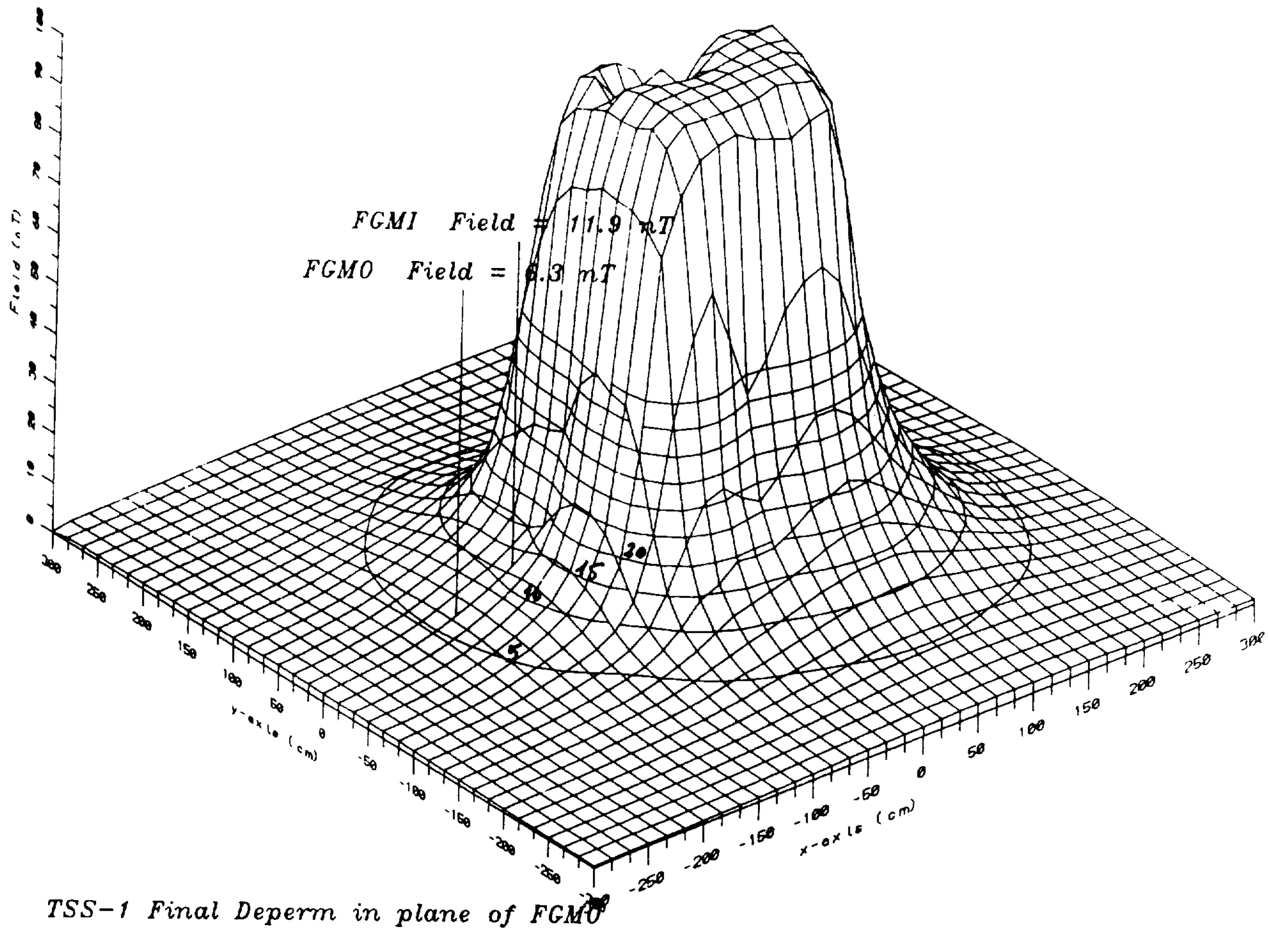


Fig. 11 - GANEW Synthetic Satellite Model Output (Tridimensional)

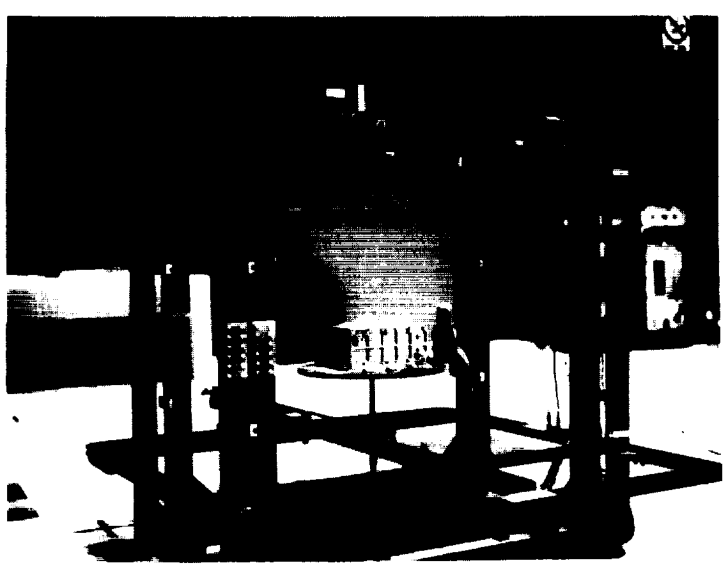

Fig. 12 - Typical TSS Unit Test

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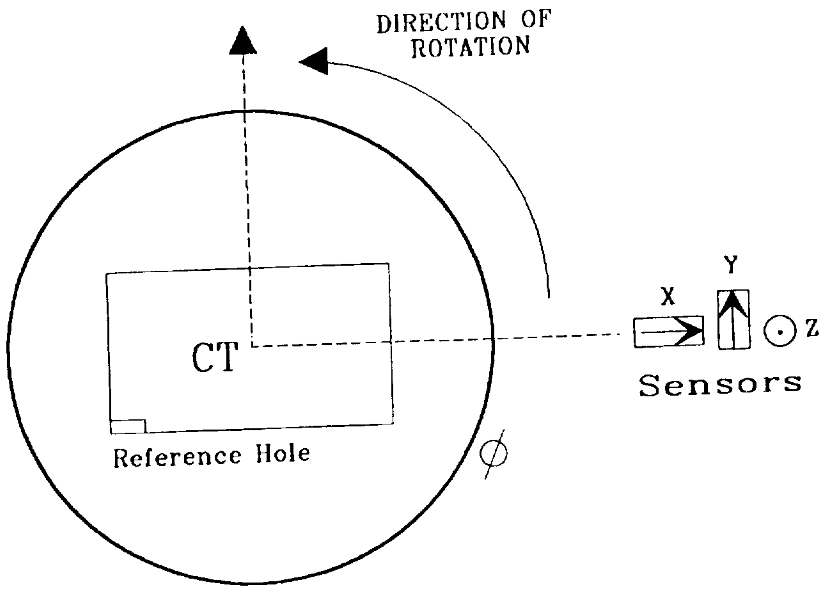


Fig. 13 - Test Set-up Sketch

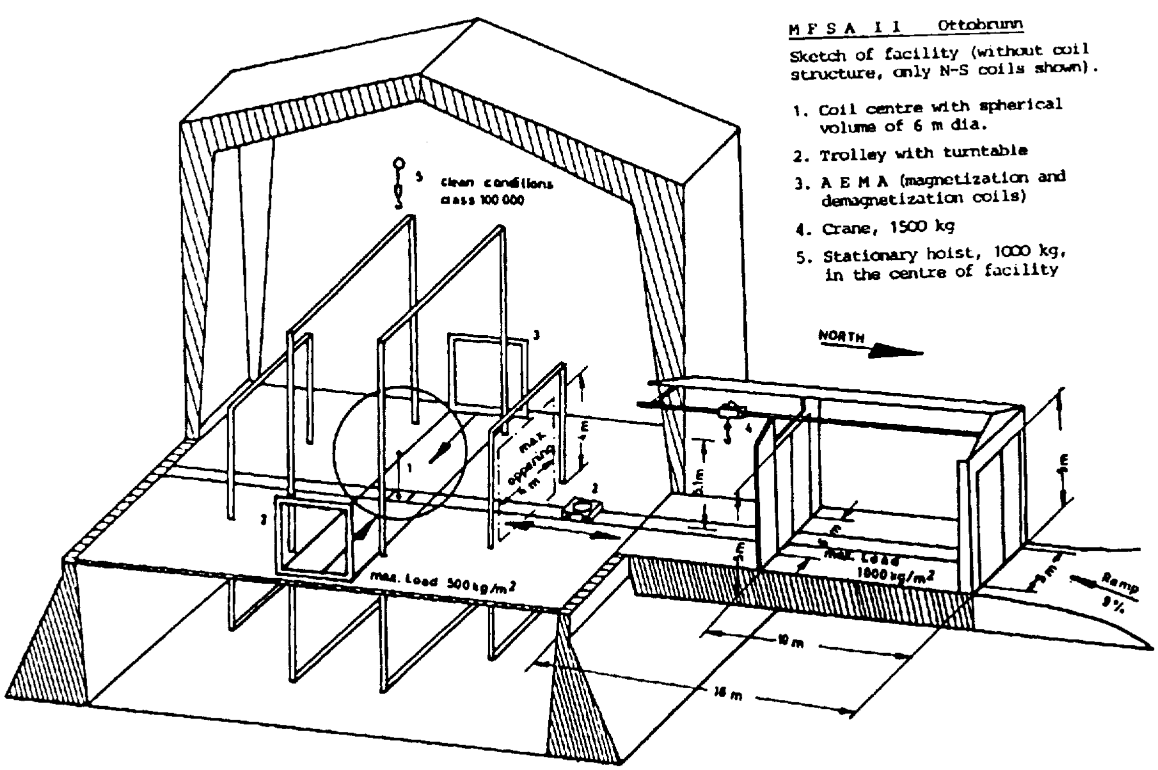


Fig. 14 - IABG MSFA II Magnetic Test Facility

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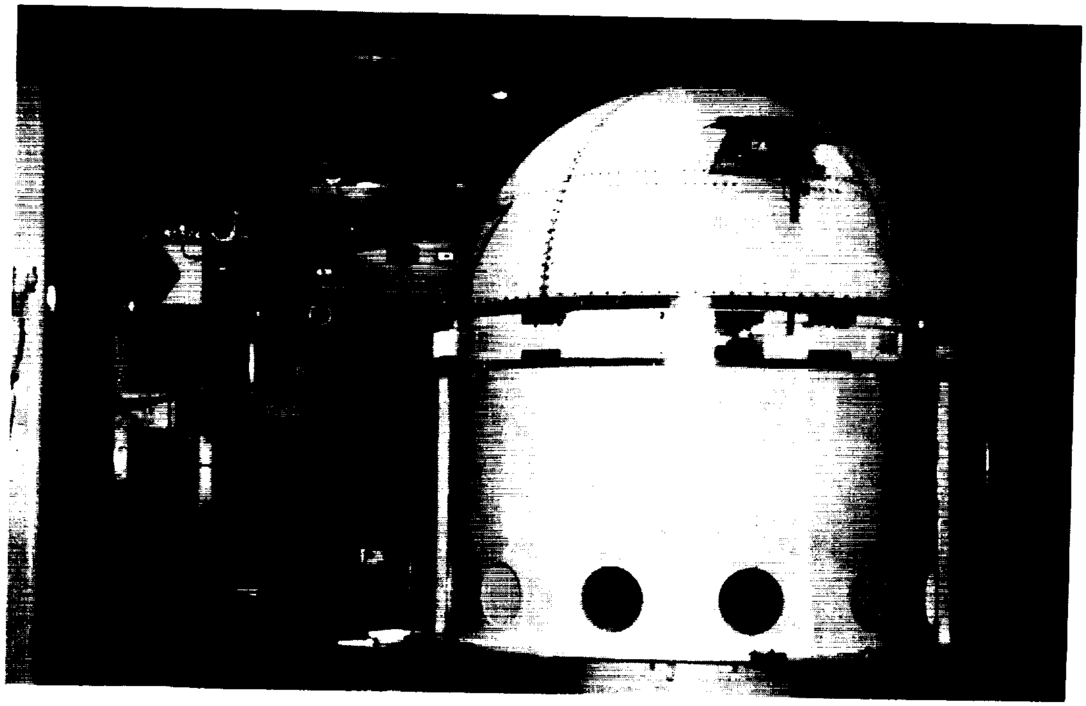

Fig. 15 - TSS-S FU Magnetic Cleanliness Test Set-up

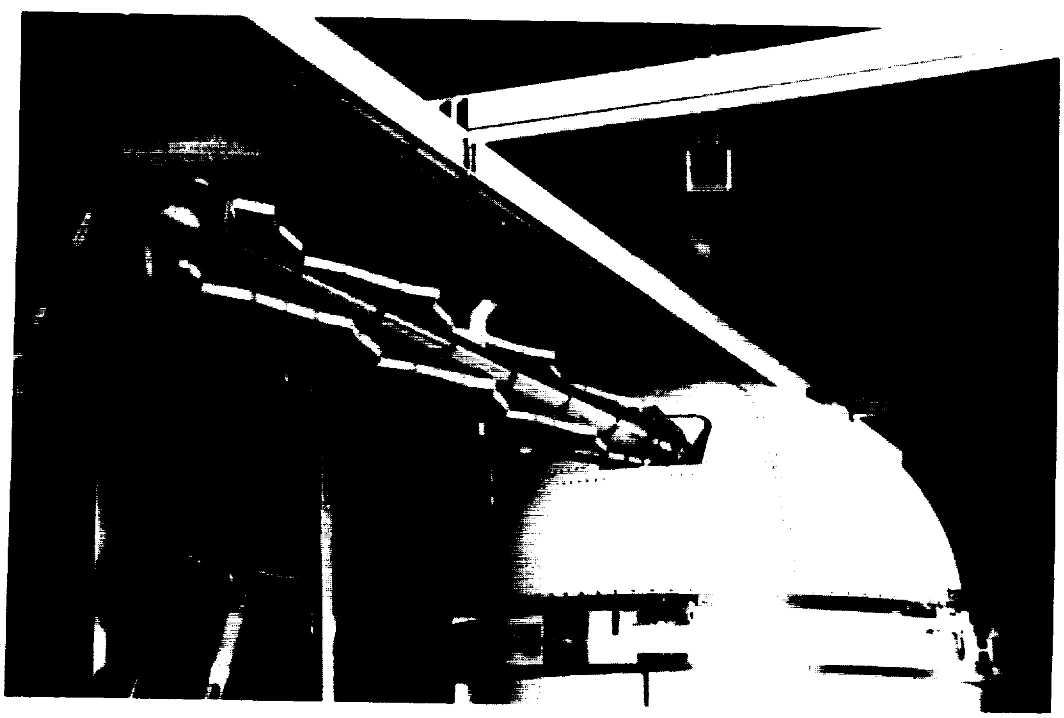

Fig. 16 - TSS-S FU Test Configuration During DRBD/A Boom Sniff Test



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Coordinate system = IABG Test Coordinates
To obtain Spacecraft coordinates change sign of Bx and By
Only Probes 3 and 4 used (probes adjacent to FGMO)
Rot = Rotational Measurements 360 deg, step=10 deg
Scan = Rotational Scan plus minus 20 deg, step=5 deg
li = Linear Interpolation between Field Measurements of Probes 3 and 4
Model = Optimal Multiple Dipole Model

| IABG | TSS Magnetic State | Mode | Data Source | Field at FGMO location (nT) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Bx | By | Bz | B |
| Run 2 | As Received 1 before local deperm | Rot | Model 2 | -25.8 | 12.3 | 5.2 | 29.1 |
| | | | Data li | -29.4 | 12.7 | 4.2 | 32.3 |
| Run 3 | As Received 1 | Scan | Data li | -29.6 | 12.8 | 4.1 | 32.5 |
| Run 4 | As Received 2 after local deperm | Rot | Model 4 | -25.8 | 12.3 | 4.8 | 28.9 |
| | | Rot | Data li | -29.6 | 11.2 | 1.6 | 31.7 |
| Run 6 | Deperm 1 | Scan | Data li | -24.7 | 9.9 | 5.3 | 27.1 |
| Run 7 | Deperm 1 after Rope exp. cleaned | Rot | Model 7 | -22.1 | 10.0 | 5.2 | 24.8 |
| | | Rot | Data li | -24.7 | 9.9 | 5.3 | 27.1 |
| Run 8 | Perm X 1 Gauss | Scan | Data li | -27.1 | 9.7 | 4.9 | 29.2 |
| Run 9 | Perm X 2 Gauss | Scan | Data li | -27.7 | 10.2 | 5.1 | 29.9 |
| Run 11 | Perm X 3 Gauss | Scan | Data li | -28.8 | 9.7 | 4.7 | 30.8 |
| Run 12 | Perm X 5 Gauss | Scan | Data li | -32.6 | 9.2 | 4.1 | 34.1 |
| | Perm X Susc. 5G | | Calcul. | -7.9 | -0.7 | -1.2 | 8.0 |
| Run 13 | Perm Y 1 Gauss | Scan | Data li | -29.5 | 11.3 | 4.0 | 31.9 |
| Run 14 | Perm Y 2 Gauss | Scan | Data li | -29.1 | 11.5 | 4.6 | 31.6 |
| Run 15 | Perm Y 3 Gauss | Scan | Data li | -27.6 | 12.2 | 4.2 | 30.5 |
| Run 16 | Perm Y 5 Gauss | Scan | Data li | -25.6 | 14.9 | 4.5 | 29.9 |
| | Perm Y Susc. 5G | | Calcul. | -0.9 | 5.0 | -0.8 | 5.1 |
| Run 17 | Perm Z 1 Gauss | Scan | Data li | -25.7 | 13.2 | 4.6 | 29.3 |
| Run 18 | Perm Z 2 Gauss | Scan | Data li | -24.9 | 12.6 | 6.0 | 28.5 |
| Run 19 | Perm Z 3 Gauss | Scan | Data li | -24.9 | 12.2 | 6.7 | 28.5 |
| Run 20 | Perm Z 5 Gauss | Scan | Data li | -25.9 | 11.3 | 8.8 | 29.6 |
| | Perm Z Susc. 5G | | Calcul. | -1.2 | 1.4 | 3.5 | 4.0 |
| Run 21 | Perm Z 5 Gauss | Rot | Model 21 | -23.7 | 11.2 | 7.2 | 27.2 |
| | | Rot | Data li | -25.6 | 11.3 | 8.9 | 29.3 |
| Run 22 | Deperm 2 | Rot | Model 22 | -22.2 | 9.2 | 5.7 | 24.7 |
| | | Rot | Data li | -25.1 | 12.2 | 8.0 | 29.0 |
| Run 23 | Deperm 2 | Scan | Data li | -25.0 | 12.1 | 8.3 | 29.0 |
| Run 24 | Stray alone | Scan | Data li | -0.7 | -1.5 | 0.0 | 1.7 |
| | Deperm 2 + Sray | | Calcul. | -25.7 | 10.6 | 8.3 | 29.0 |
| Run 26 | Deperm 3 | Scan | Data li | -22.1 | 17.0 | 3.0 | 28.0 |
| Run 27 | Deperm 3 | Rot | Model 27 | -20.9 | 13.2 | 4.8 | 25.2 |
| | | Rot | Data li | -22.2 | 16.7 | 2.8 | 27.9 |
| Run 29 | Deperm 4 +Transponder + Gyros | Rot | Model 29 | -22.0 | 12.8 | 4.8 | 25.9 |
| | | Rot | Data li | -23.3 | 16.6 | 3.8 | 28.8 |
| Run 30 | Deperm 4 | Scan | Data li | -23.2 | 16.4 | 3.5 | 28.7 |

Fig. 17 - TSS-S FU Magnetic Cleanliness Test Results

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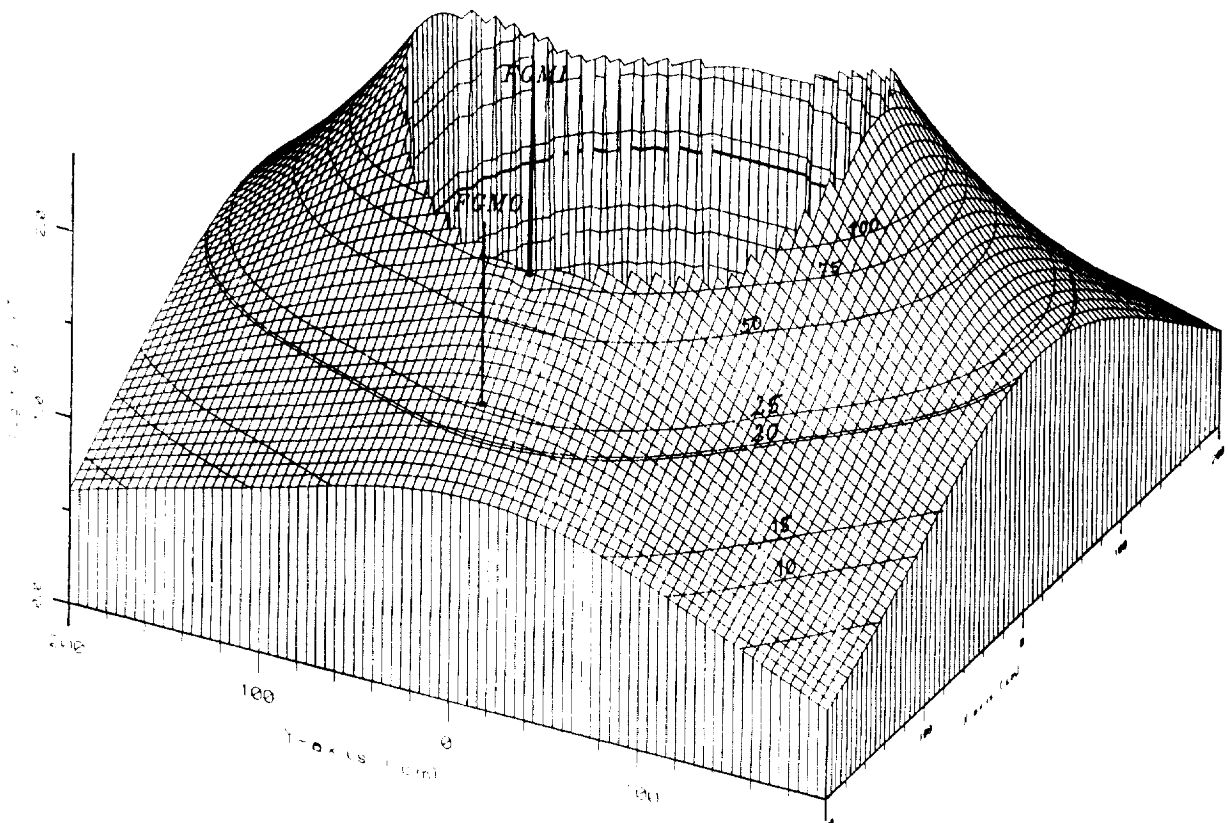


*TSS-1 Deperm 4, Field in x,y-plane through FGM0*

**Fig. 18 - TSS-S FU Final Magnetic Field distribution**