

## MISSION OPERATIONS DATA ANALYSIS TOOLS FOR MARS OBSERVER GUIDANCE AND CONTROL

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### ABSTRACT

Mission operations for the Mars Observer (MO) Project at the Jet Propulsion Laboratory were supported by a variety of ground data processing software and analysis tools. Some of these tools were generic to multi-mission spacecraft mission operations, some were specific to the MO spacecraft, and others were custom tailored to the operation and control of the Attitude and Articulation Control Subsystem (AACS). The focus of this paper is on the data analysis tools for the AACS. Four different categories of analysis tools are presented; with details offered for specific tools. Valuable experience was gained from the use of these tools and through their development. These tools formed the backbone and enhanced the efficiency of the AACS Unit in the Mission Operations Spacecraft Team. These same tools, and extensions thereof, have been adopted by the Galileo mission operations, and are being designed into Cassini and other future spacecraft mission operations.

### INTRODUCTION

From launch on Sept. 25, 1992 to Aug. 21, 1993, three days to Mars Orbit Insertion, the Mars Observer (MO) Project was supported by an efficient mission operations Spacecraft Team. This team was made up of units of engineers / analysts with cognizance over the different functions/ subsystems of the spacecraft, including the Attitude and Articulation Control Unit (AACS), Information Unit, Flight Software Unit, Telecommunication Unit, Power Unit, Thermal Unit, Propulsion Unit and Systems Unit.

The Spacecraft Team was responsible for the (i) monitoring, (ii) analysis, and (iii) command & control of the spacecraft. Monitoring included real-time watching of spacecraft telemetry; depending on the criticality of the activities, 3-shift 24-hour operations were often required. Off-shift (and also prime-shift) monitoring and command radiation was always done by another around-the-clock team in the Flight Operations Office.

Analysis consisted of real-time, near real-time, and off-line analysis. This included routine data analysis, spacecraft characterization, health/welfare tracking of the spacecraft and spacecraft hardware, incident/surprise/anomaly data analysis, contingency planning, update/design/development/testing of ground software as well as of flight software. .

Command & control was equated with the on-ground planning and execution of preplanned sequences or discrete commands, that were uplinked ahead of time, or uplinked in real-time. These commands and controls were mostly high-level, even though there were times when discrete single-event commands were uplinked, such as hardware turn-on, turn-off and mode-transitions. For an advanced, autonomous spacecraft like MO, the real-time sub-second and sub-mini-second control was naturally executed on-board under the flight software control. In the present context, the sequence design and analysis activities leading to the single and/or sequence command, were considered to be "command & control" activities.

In AACS mission operation, monitoring, analysis, and control/command activities were dedicated to the following major task areas:

- periodic parameter/catalog updates
- routine health and state monitoring, tracking and trending
- maneuver ( $\Delta V$ ) design, and post-maneuver analysis
- hardware calibration design, and post-calibration analysis
- science experiment/sequence design, and post-sequence analysis
- spacecraft event/sequence design, and post-sequence analysis
- real-time operation and support (including maneuvers, calibration sequences, science sequences, command & sequence uploads, flight software uploads, subsystem/spacecraft activities)
- flight control software updates
- testing and verification
- anomaly investigation
- nominal inter-subsystem coordination, planning and interface
- project level coordination, interface and reporting,

Automated tools were indispensable for the monitoring, analysis, command & control of AACS. Tools included displays, list pages, graphical plots, statistics charts, computer programs, data retrieval software, data formatting software, data packaging software, data generation software, data analysis software, mathematics libraries, special graphics analysis tools, command and sequence generation programs, controls simulation software, and spacecraft system simulation/verification test hardware/software (laboratories).

Due to human resource limits, the need for quick turn-around time, and more importantly, the requirement for consistency and correctness of the products, numerous analysis tools were developed. Some tools were general-purpose, and some were custom-tailored to AACS. This paper will categorize and describe these analysis tools.

## JPL's MGDS (Multi-mission Ground DATA System) - AMMOS

At the Jet Propulsion Laboratory (JPL), MGDS refers to the hardware/software that supports multi-mission telemetry processing and spacecraft commanding. MGDS consists of a network of workstation-class, multi-tasking computers using standard operating systems, software applications and tools. The overall operations, i.e. MGDS plus workforce, processes, procedures and facilities, constitute the Advanced Multi-Mission Operations Systems (AMMOS).

The MO AMMOS hardware and software system provided the integrated telemetry data retrieval, front-end processing, and archiving functions. While not attempting to describe the AMMOS capabilities which are described in detail in (ref. 1), this paper will highlight the customization of the AMMOS real-time on-line telemetry analysis tools for MO AACS mission operations,

AMMOS is an extension, improvement and modernization of the earlier JPL Space Flight Operations Center (SFOC) for space exploration missions including Voyager and Viking. The 1989 Magellan mission to Venus was the first JPL project to utilize AMMOS in its mission operations. MO, the 1992 mission to Mars, was the second one. Recently, the Galileo mission to Jupiter (launched in 1989) has been converted to AMMOS. Mars Global Surveyor to Mars 1996 and Cassini to Saturn 1997 will also utilize AMMOS.

## MO DATA ANALYSIS TOOLS

To perform the activities of monitoring, analysis, and command & control for the major AACS functional tasks discussed above, four (4) categories] of data analysis tools were used for MO mission operations:

### Cat A. Real-Time On-line Telemetry Data Analysis Tool

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<sup>1</sup>The terms Cat A, Cat R, etc. should not be confused with the JPL formal terms of Class A, Class R, etc., referring to the space-flight qualification level of software.

- Cat B. Non-Real-Time Telemetry Data Analysis Tools
- Cat C. Non-Real-Time Data Analysis and Performance Evaluation Tools
- Cat D. Non-Real-Time Data Generation & Viewing Tools

Cat A refers to the processing of "live" real-time telemetry that was broadcasted by AMMOS for real-time monitoring.

Cat B refers to the "near-real-time" and "off-real-time" analysis. "Near-real-time" typically involved the retrieval of telemetry data as recent as a few minutes old. "Off-real-time" referred to the retrieval of "archived data" which are day-old, week-old or older.

Cat C refers to the design and analysis tools, mostly for the generation of design parameters, files, catalogs etc., which form part of the input files and parameter updates to be included in uplink commands and sequences.

Cat D refers to miscellaneous AMMOS processes for the data retrieval, extraction, packaging, reformatting, viewing, file generation, sequence generation with constraints checking, and miscellaneous workstation utilities.

(No attempt is made in this paper to discuss the spacecraft system and subsystem verification/test laboratory. )

### Cat A Tools

Real-Time On-line Telemetry Data Analysis Tools were supplied by AMMOS on AMMOS workstations. Major tools were: DMD (Data Monitor and Display), MO\_Browser, CV\_(Command and Verification)\_Monitor.

DMD provides standard and customizable displays for users to view channelized engineering telemetry and other mission data. A number of display formats are available, including list pages, "printer pages", channel-vs-time plots, channel-vs-channel plots. A whole set of software modules caters to customized data unit expansion, alarm-alerting and display setup.

MO\_Browser provides individual stream data viewing down to the bit level. This tool is designed and used by MGDS data analysts more often than by spacecraft mission operations engineers.

CV\_Monitor provides real-time monitoring of real-time or sequenced commands. The MO flight software is designed to return verification messages upon the receipt of commands.

### Cat B Tools

Most of the non-Real-Time Telemetry Data Analysis Tools were supplied by AMMOS, and the rest customized by AACS engineers.

AMMOS tools facilitate data retrieval, reformatting, plotting, statistical summary, and archiving. These tools include query2plot, ecsv2plt, ecsv2ctab, ecsv2drf, drf2ecsv, ecsv2sum, ecsvmerge, oplot, xvmpplot, ecsview etc. "ecsv", "ctab", "drf" refers to the data format of comma-separated-value, column-table, and data-row-file files.

Typically, the above tools are PERL scripts. (PERL is an interpreted language with features very similar to UNIX C-shell commands. ) A prespecified set of channels of data can be queried from the AMMOS Central Data Base or from UNIX files, after which the channelized data is run through DMD and then output to a file. The three ecsv, ctab, drf formatted files may be the end-products or may be further processed.

A library of mathematical functions is very handy for the post-processing of the drf files. Examples are normalization, quaternion manipulation, trigonometric functions, and coordinate transformation functions. Statistics can also be computed, merged with files of earlier dates, and archived for trending purposes,

Plotting routines includes oplot, xvmpplot and others. Multiple channels versus time, or channel vs channel can be plotted, A special tool is available to view the ecsv files in tabulated forms; this ecsview tool also has editing and filtering capabilities.

A custom graphics program, the MOBALL<sup>2</sup>, is a geometrical representation tool. MOBALL draws the celestial sphere with the view from outside the sphere looking in, where the MO spacecraft lies at the center of the sphere. J2000 coordinates are used to draw the latitudes and longitudes. Hitting the left, right, up, down arrow keys correspondingly change the view point.

MOBALL was frequently used for viewing the geometry of the MO spacecraft relative to celestial bodies, i.e. Mars, Jupiter, Earth, Sun and stars. A simple wire-frame model of MO at the center of the sphere offered good insight for spacecraft pointing design, instrument pointing occultation analysis, thermal protection pointing, celestial body motion analysis, and star field analysis.

Analyzing star fields was done weekly and sometimes daily, using MOBALL. MCS was designed with a Celestial Star Assembly to collect star crossings for the estimation of spacecraft attitude; star crossings repeated every 100 minutes, MO's spin period. Two star catalogs, one called "ANS"-pointing, and one called sun-pointing, were uploaded to the spacecraft every week. Star field plots on the MOBALL were indispensable tools for star tracking, particularly for the evaluation of loss-of-attitude anomalies.

Another set of custom data analysis tools is embedded with AMMOS DMD. "Derived channels" can be computed in real-time and triggered by their "parent channel". Examples of derived channels are "bit decomposition" of "digital state" channels; "mnemonics assignment" child-channels for numeric-state parent-channels; unit scaling upon trigger-state; coordinate transformation channel (from spacecraft body coordinates to J2000 coordinates); performance-index evaluation from a set of parent-channels. One very informative channel of the last type was: "quaternion\_delta of SCP\_in\_control vs SCP\_not\_in\_control". (The Standard Control Processor, SCP, was MO's flight computer.)

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<sup>2</sup>MOBALL is a C-program written by S. Collins, a MO AACCS engineer.

### Cat C Tools

Non-Real-Time Data Analysis and Performance Evaluation Tools were analysis tools to generate design parameters, files, catalogs etc., usually included in uplink commands and sequences.

A Performance Analysis System (PAS) was developed by General Electric Astro-Space Division (GE-ASD), the MO spacecraft contractor for JPL. PAS programs include ephemeris generation, star catalog generation, momentum unloading prediction, roll angle optimization for solar panel pointing (e.g. during a maneuver with or without pitching), spacecraft mass change estimates caused by maneuvers, propellant consumption, thruster characterization, etc. These programs were designed to input data files in predefine formats and output data files in predefine formats, according to MO Project specifications. The intent was to combine the analysis and file generation into one "flight-certified Class A software" process.

PAS software runs on AMMOS workstations (UNIX platforms), with X window and Motif graphics package (for the Graphical User Interface), and interfaces with C and Fortran 77 modules.

GE-ASD also provided MOSIM, a controls dynamics and simulation software package. MOSIM has better dynamics simulation, but has slightly different fidelity as the spacecraft verification/test laboratory (VTL) simulation; in VTL, flight computer hardware and software are duplicated, with flight-like interfaces to spacecraft sensors and actuators. MOSIM is written in Fortran, and runs on a Macintosh computer; it runs faster than the real-time rate at which the VTL simulation runs. (VTL was also developed by CIZ-ASD.)

Customized database spreadsheet programs are part of the Cat C analysis tools. For MO maneuver analysis, a large EXCEL™ workbook was devised with five spreadsheets linked together. Spacecraft parameters such as thruster moment arm, engine I<sub>sp</sub>, spacecraft mass and inertia properties, controller gains, desired delta\_V, burn

times, etc. are strategically designed into "static" data blocks, input data entry cells, and output data cells. This process was to standardize and automate the frequent maneuver analysis (Mars Orbital Ops require maneuvers at 2-3 week intervals, )

### Cat D Tools

Non-Real-Time Data Generation & Viewing Tools for data retrieval, extraction, packaging, reformatting, viewing, file generation include AMMOS programs: TOT (Telemetry Output Tool to query data), CDB\_WOTU (Central Database Window-On-The-Universe: file retrieval and deposit), MO\_GAP\_VIEW (data dropout/ gap review), SOE\_VIEW (Sequence-of-events viewing and editing), SCLK-to-SCET (spacecraft time conversion, etc. User friendly GUI's accompany these programs,

Sequence and command design tools include SEQGEN (sequence generation), MOCHECK (MO constraints and flight rules checking), SASFGEN (Spacecraft Activity Sequence File Generation), INCON and FINCON (incoming and outgoing spacecraft configuration listing, i.e. before and after a sequence), etc.

### Tools & Analysis for Special Mention

Among the above data analysis tools, a few are worth special mention and illustration. Figure 1 shows the DMD "ZO-plots" page. Some seventy channels are grouped and color coded in this page of nineteen plots. With a time scale over the period of 100 minutes (the spin period of MO), a nominal signature on this 20-plot display was readily associated with a nominally behaving spacecraft, In fact, this was a daily monitoring and reporting tool!

One major feature that makes DMD such a powerful real-time and off-real-time tool is its capability to derive child-channels from parent-channel(s) in real-time. For AACS, 106 child-channels were derived from some 530 parent-channels<sup>3</sup>. Detailed designs are documented in the MCS Telemetry Dictionary (ref. 2).

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<sup>3</sup>These numbers apply to the "SCP-in-control"; similar numbers apply to the "SCP-not-in-control". There are extra telemetry for non-SCP data.

User friendly displays are indispensable particularly for real-time monitoring of a spacecraft as complex as MO, where multiple (hundreds of) hardware and software parameters had to be monitored. Man-machine interface techniques and human engineering skills used in display layouts, telemetry channel numbering, mnemonics design, and above all, channel grouping by functional groups and display "rooms" were the key to success in MO. The development of MCS Telemetry Dictionary (ref. 2) was instrumental to this design; a similar development (ref. 3) for the Cassini spacecraft also illustrates the methodology. Table 1 is an extract from the AACS Telemetry Dictionary.

Figure 2 illustrates MOBALL in a sequence design of the Thermal Emission Spectrometer (TES) instrument on MO. The spacecraft wire-frame model provides, among other analysis features, a visual representation of the spacecraft and the TES instrument pointing relative to the Sun and Mars. The sequence was designed to calibrate TES using Mars in its field-of-view, and was successfully executed on Aug. 1, 1993. Details of the sequence design and the use of MOBALL can be found in (ref. 4).

Star catalog generation (weekly) and analysis (weekly; real-time by-demand) were facilitated by star field maps and planet trajectory maps, drawn with MOBALL. Figure 3 shows such a star field map. The methodology in star field analysis can be found in (ref. 5). Also, during the last ten weeks of MO, after a flight software change providing the downlink of the identified stars in the Celestial Star Assembly star identification software, star sightings and identifications were analyzed and tabulated. The latter was meant to calibrate the Standard Star Catalog provided by Honeywell after all the 1801 stars in the catalog were all sighted,

While due mention should be made to the Performance Evaluation System (PAS) and the spreadsheet rendition of the maneuver analysis tool, page limitation does not permit further discussion in this paper. More details could be found in (ref. 6).



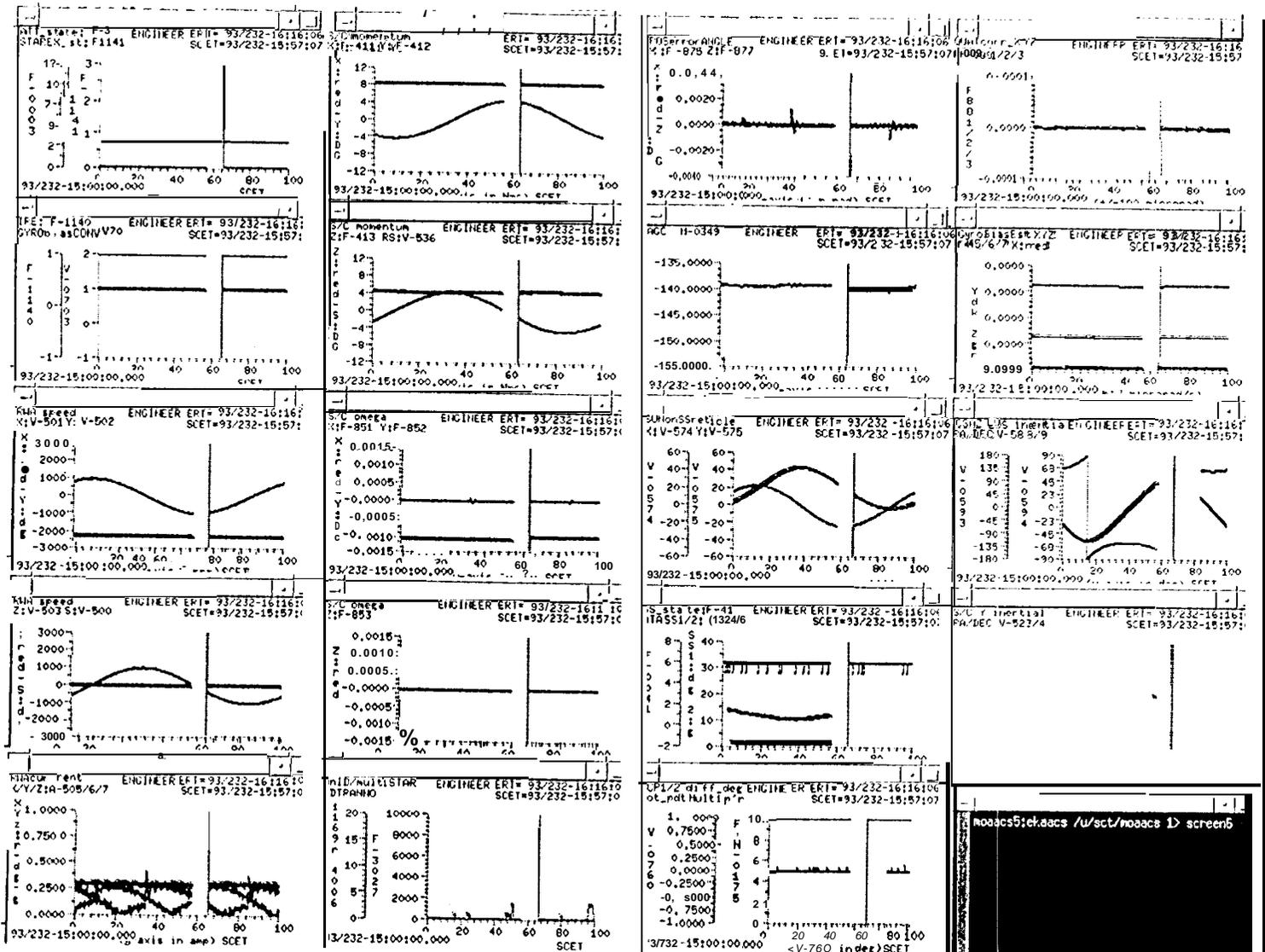


Figure 1. "20-plots" Composite Page, Plotting Major MO AACS States

(Plot #1 on left-hand upper corner, down the column to Plot#5, etc., Plot #16 through Plot#19 on the right most column)

(Original display in color, representing a maximum of 4 channels per plot.)

(Horizontal scale in SCET, Spacecraft Event Time; period of 100 minutes= MO spin period)

- |   |   |  |  |
|---|---|--|--|
| P1. Attitude_State<br>STAR_EX_State             | P6. S/C_Momentum: X; Y                    | P h. (Attitude)_POS_error:<br>x; Y; Z          | P16. Quaternion_Correct'n:<br>x; Y; Z        |
| P2. Inertial_Ref_Acquired<br>GyroBias_Converged | P7. S/C_Momentum: Z;<br>S/C_Mom: RSS(X+Z) | P12. AGC (db gain)                             | P17. GyroBias_Estimate:<br>x; Y; z           |
| P3. RWA_Speed: X; Y                             | P8. S/C_Rate: X; Y                        | P13. Sun Sensor Reticle<br>Reading: X; Y       | P18. Celestial Sensor Ass.<br>J-2000 RA; DEC |
| P4. RWA_Speed: Z; S                             | P9. S/C_Rate: Z                           | P14. Sun Sensor State;<br>ATA:SS1; SS2         | P19. S/C Body:<br>1-2000 RA; DEC             |
| P5. RWA_Current: X; Y; Z                        | P10. UNID_Star; Multi_Star;<br>IDTRANNO   | P15. SCP1/2 diff_degree;<br>dot_pdt_multiplier | P20. "xterm" window                          |

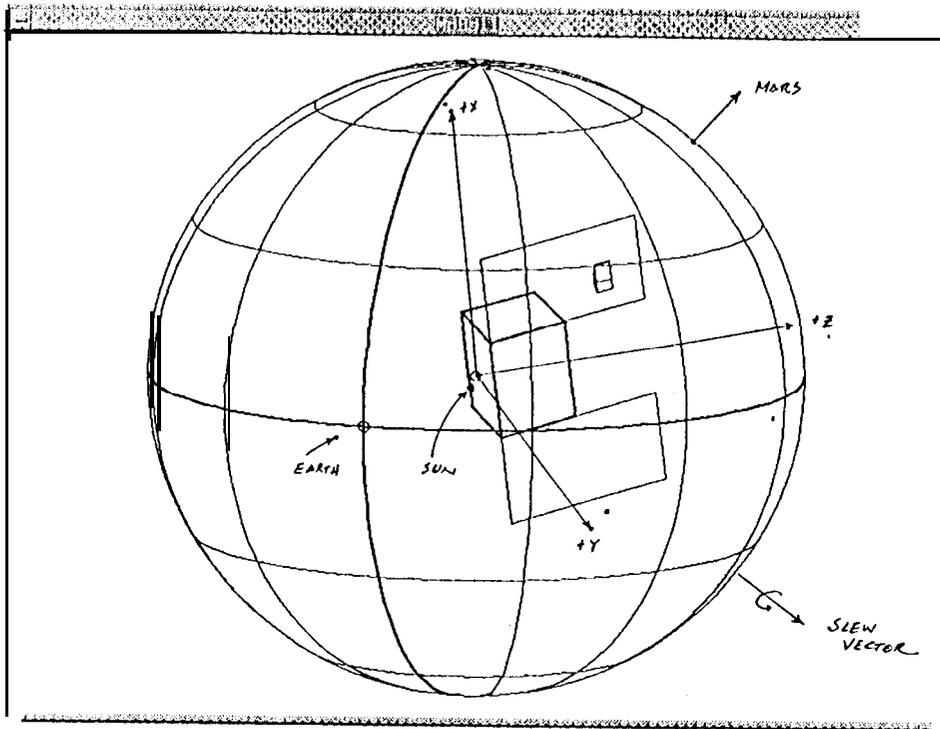


Figure 2. MOBALL Pointing Analysis - TES Instrument Calibration

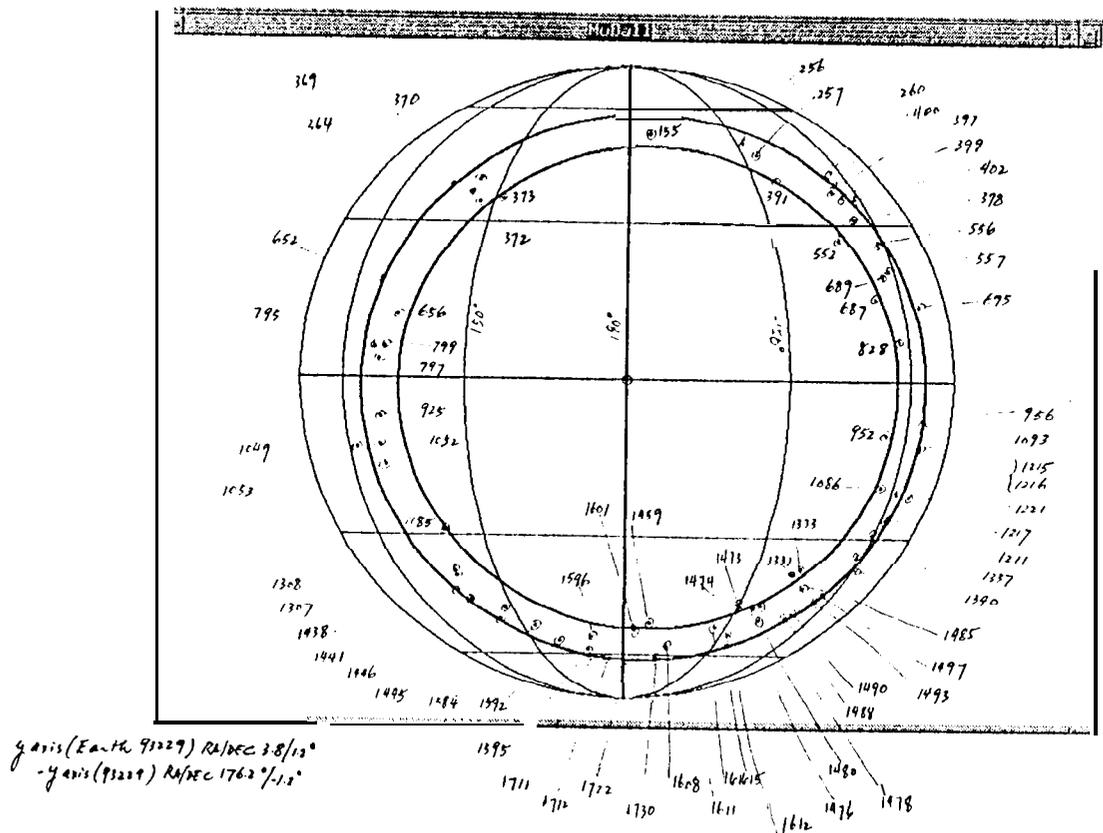


Figure 3. MOBALL Star Field Analysis -93229 ANS Star Catalog