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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-milli-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[1] of data analysis tools were used for MO mission operations:

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

[1] The terms Cat A, Cat B, etc. should not be confused with the JPL formal terms of Class A, Class B, 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, xvmplot, ecsvview 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, xvmplot 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 ecsvview tool also has editing and filtering capabilities.

A custom graphics program, the MOBALL[2], 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. AACS 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.)

[2] MOBALL is a C-program written by S. Collins, a MO AACS 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 predefined formats and output data files in predefined 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 GE-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_{sp}, 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 "20-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[3]. Detailed designs are documented in the AACS Telemetry Dictionary (ref. 2).

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 AACS 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).

[3] 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.

CLOSING REMARKS

The Mars Observer AACS mission operation was greatly streamlined with the help of the analysis tools, and above all the methodology, discussed in this paper. Some of these tools were generic to JPL's AMMOS (Advanced Multi-Mission Operations System) spacecraft mission operations, and some were specifically tailored to the Mars Observer AACS. These generic tools, and extensions of the custom-tailored tools have been infused into, and are operational in the on-going Galileo mission. They are also being designed into Cassini and other future spacecraft missions.

Acknowledgment

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

REFERENCES

1. Anon., "Multimission Ground Data System User's Guide, Vol. 1 - 4," JPL Document D-6060, Jet Propulsion Laboratory, Pasadena, Ca., USA, Jan. 1994.
2. Kan, E. P., "Mars Observer - AACS Telemetry Dictionary," IOM# MO-SCT-93-077, Jet Propulsion Laboratory, Pasadena, Ca., USA, 2/4/93.
3. Kan., E. P., "Process and Methodology of Developing Cassini G&C Telemetry Dictionary," Proc. SPACEOPS 1994, 3rd Int. Symp. on Space Mission Operations and Ground Data Systems, held at Goddard Space Flight Center, Greenbelt, Md., USA, Nov. 14-18, 1994.
4. Kan, E. P., "Mars Observer - Thermal Emission Spectrometer Calibration (TES CAL) Analysis Methodology," IOM# MO-SCT-93-203, Jet Propulsion Laboratory, Pasadena, Ca., USA, 3/24/93.
5. Kan, E. P., "Mars Observer - Analysis Behind the Generation of Weekly Star Catalogs" IOM# MO-SCT-93-136, Jet Propulsion Laboratory, Pasadena, Ca., USA, 2/26/93.
6. Kan, E. P., "Mars Observer - Mission Operations Data Analysis Tools," presentation on 8/19/93, also IOM# MO-SCT-93-563, Jet Propulsion Laboratory, Pasadena, Ca., USA, 8/25/93.

Table 1. AACS Telemetry Dictionary - sorted by Functional Groups (excerpt)

S/S	Chl#	Related Channel (or Data Type)	NAME	Category	Row	List	vdt	Safe	Emgcy	Mission	Engr	Children Channel #	Parent # (MuxAdr)	redhi	yelhi	yello	redlo
F	22	22	S/C_State	SC_RDMN	1	20	20				s(FN)						
F	37	37	CIU_flags	SC_RDMN	2	20	20	f(F)	f(F)	f(FN)	f(FN)	3119/20/27/34/etc					
F	3134	3134	Contingency_mode_SCP1	SC_RDMN	3	20	20	f(F)P	f(F)P	f(FN)P	f(FN)P		37				
C	2	2	CIU_SCP_in_control	SC_RDMN	4	20	20		112	4	0.5						
H	5	5	Telemetry_bit_rate	SC_RDMN	5	20	20		X	X	X						
H	25	25	Telemetry_mode	SC_RDMN	6	20	20		X	X	X						
V	52	52/53	Mission_phase	SC_RDMN	7	20	20		112Pbu	16P	2P		C-33/5/7				
F	3113	3113	REDMAN_switch_status_cont	SC_RDMN	8	20	20	f(F)	f(F)	m(F)*(N)	m(FN)	1103/04/10/13/etc					
F	3	3	ATT_State	AACStlm	1	17	17		f(F)	m(F)*(N)	m(FN)						
F	3102	3102	Packed_Attitude	AACStlm	2	17	17		f(F)	m(F)*(N)	m(FN)	61/64/75/85/99;4007					
F	4007	4007	New_Att_control_mode_entry	AACStlm	3	17	17		f(F)P	m(F)P	m(FN)P		3102 b10				
F	1140	1140	STAREX_inertial_ref_establ'ed	AACStlm	4	17	17		f(F)P	m(F)P	m(FN)P		3102 b 0				
F	427	427/8/9	CMD'd_rate_X	AACStlm	26	17	17			m(F)	m(FN)						
F	4093	4093	Sun_SUBM	AACStlm	29	17	17				s(FN)						
F	41	41	SS_State	AACStlm	30	17	17	f(F)	f(F)	m(F)	m(FN)						
F	3109	3109	STAREX_status_word	AACStlm	31	17	17			m(F)	m(FN)	V-700/.../711					
F	843	843/.../6	Filter_Body_Quat_1	AACStlm	32	17	17		f(F)	f(FN)	f(FN)	V520..33; 580..94;760					
F	851	851/2/3	Filter_Body_Rate_X	AACStlm	36	17	17		f(F)	m(F)*(N)	m(FN)						
F	875	875/6/7	Pos_Error_Angle_X	AACStlm	39	17	17	f(F)	f(F)	m(F)*(N)	m(FN)						
F	411	411/2/3	SYST_MOM_X	AACStlm	42	17	17	f(F)		m(F)	m(FN)	V-535/6		12	8.8	-8.8	-12
F	412	411/2/3	SYST_MOM_Y	AACStlm	43	17	17	f(F)		m(F)	m(FN)	V-535		12	8.8	-8.8	-12
F	413	411/2/3	SYST_MOM_Z	AACStlm	44	17	17	f(F)		m(F)	m(FN)	V-535/6		12	8.8	-8.8	-12
V	535	535	SYST_MOM_RSS	AACStlm	45	17	17	f(F)P		m(F)P	m(FN)P		411/.../3		8.8	-8.8	
V	536	536	X+Z__MOM_RSS	AACStlm	46	17	17	f(F)P		m(F)P	m(FN)P		411/3		8.8	-8.8	
V	760	760	SCP1/2_deltaQUAT	AACStlm	47	17	17			f(F)Ps(N)F	f(FN)P		FN-843..5	0.5	0.1	-0.1	-0.5
M	349	349	AGC downlink	AACStlm	\	\	\										
F	3064	3064	Maneuver_in_progress	deltaV	1	4;14	14		f(F)P	m(F)P	m(FN)P		3102				
F	2047	2047	Maneuver_flag	deltaV	2	14	14			m(F)	m(FN)						
F	2048	2048	Maneuver_status	deltaV	3	14	14			m(F)	m(FN)						
F	3924	3924	Thruster_Configuration	deltaV	4	14	14			s(F)	s(FN)						
F	430	430/1/2	DeltaV_X	deltaV	5	4;14	14			s(F)	s(FN)						
F	431	430/1/2	DeltaV_Y	deltaV	6	4;14	14			s(F)	s(FN)						
F	432	430/1/2	DeltaV_Z	deltaV	7	4;14	14			s(F)	s(FN)						
F	3177	3177/82/87/92	RWA_power_on_X	RWA	1	1;11	11	f(F)P	f(F)P	m(F)P	m(FN)P		1841/.../4				
F	3182	3177/82/87/92	RWA_power_on_Y	RWA	2	1;11	11	f(F)P	f(F)P	m(F)P	m(FN)P		1841/.../4				
F	4069	4069	RWA_configuration	RWA	5	11	11										
F	3178	3178/83/88/93	RWA_power_limited_X	RWA	6	11	11	f(F)P	f(F)P	m(F)P	m(FN)P		1841/.../4				
etc	etc	etc	etc	etc	etc	etc	etc	etc	etc	etc	etc	etc	etc	etc	etc	etc	etc

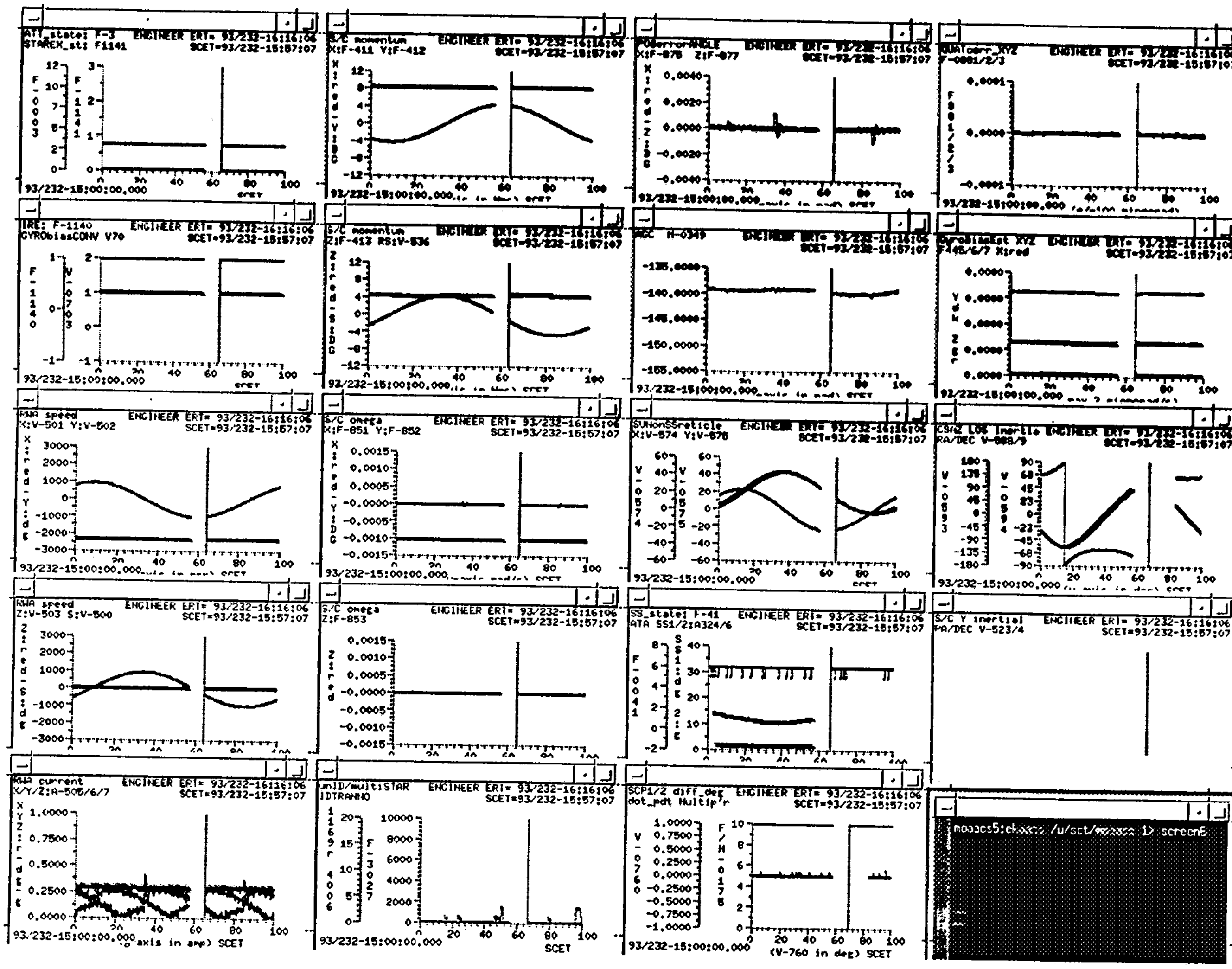

Figure 1. "20-plots" Composite Page, Plotting Major MO AACS States
(Plot #1 on left-hand upper corner, down the column to Plot#5,
etc., Plot #16 through Plot#19 on the right most column)
(Original display in color, representing a maximum of 4 channels per plot.)
(Horizontal scale in SCET, Spacecraft Event Time; period of 100 minutes = MO spin period)

P1. Attitude_State STAREX_State
P2. Inertial_Ref_Acquired GyroBias_Converged
P3. RWA_Speed: X; Y
P4. RWA_Speed: Z; S
P5. RWA_Current: X; Y; Z
P6. S/C_Momentum: X; Y
P7. S/C_Momentum: Z; S/C_Mom: RSS(X+Z)
P8. S/C_Rate: X; Y
P9. S/C_Rate: Z
P10. UNID_Star; Multi_Star; IDTRANNO
P11. (Attitude)_POS_error: X; Y; Z
P12. AGC (db gain)
P13. Sun Sensor Reticle Reading: X; Y
P14. Sun Sensor State; ATA: SS1; SS2
P15. SCP1/2 diff_degree; dot_pdt_multiplier
P16. Quaternion_Correct'n: X; Y; Z
P17. GyroBias_Estimate: X; Y; Z
P18. Ceslestial Sensor Ass. J-2000 RA; DEC
P19. S/C Body : J-2000 RA; DEC
P20. "xterm' window

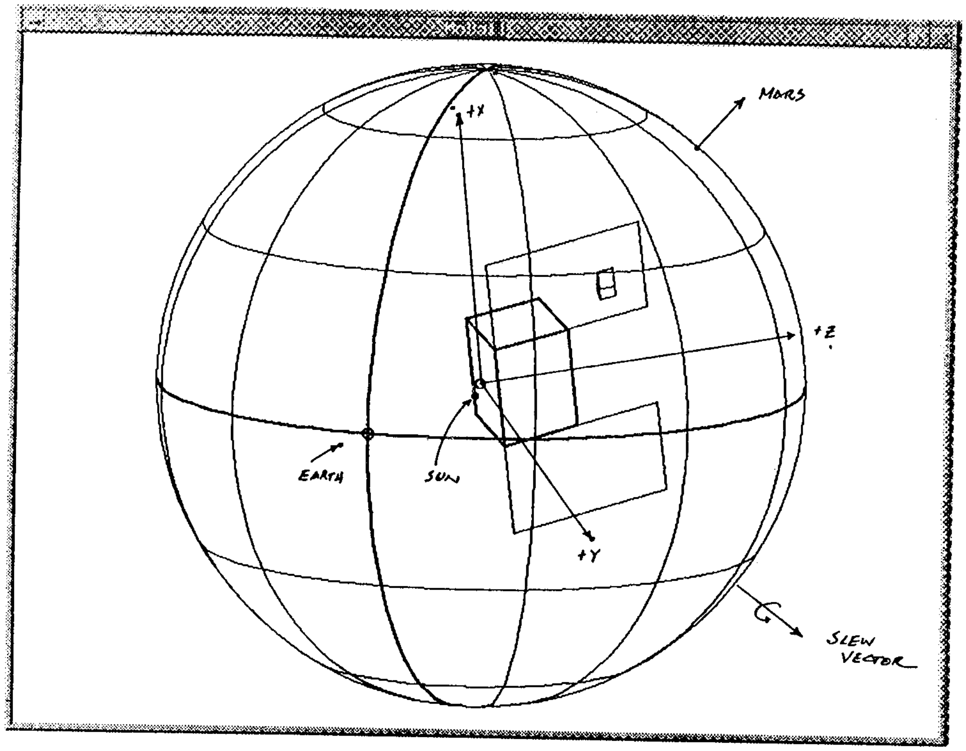

Figure 2. MOBALL Pointing Analysis - TES Instrument Calibration

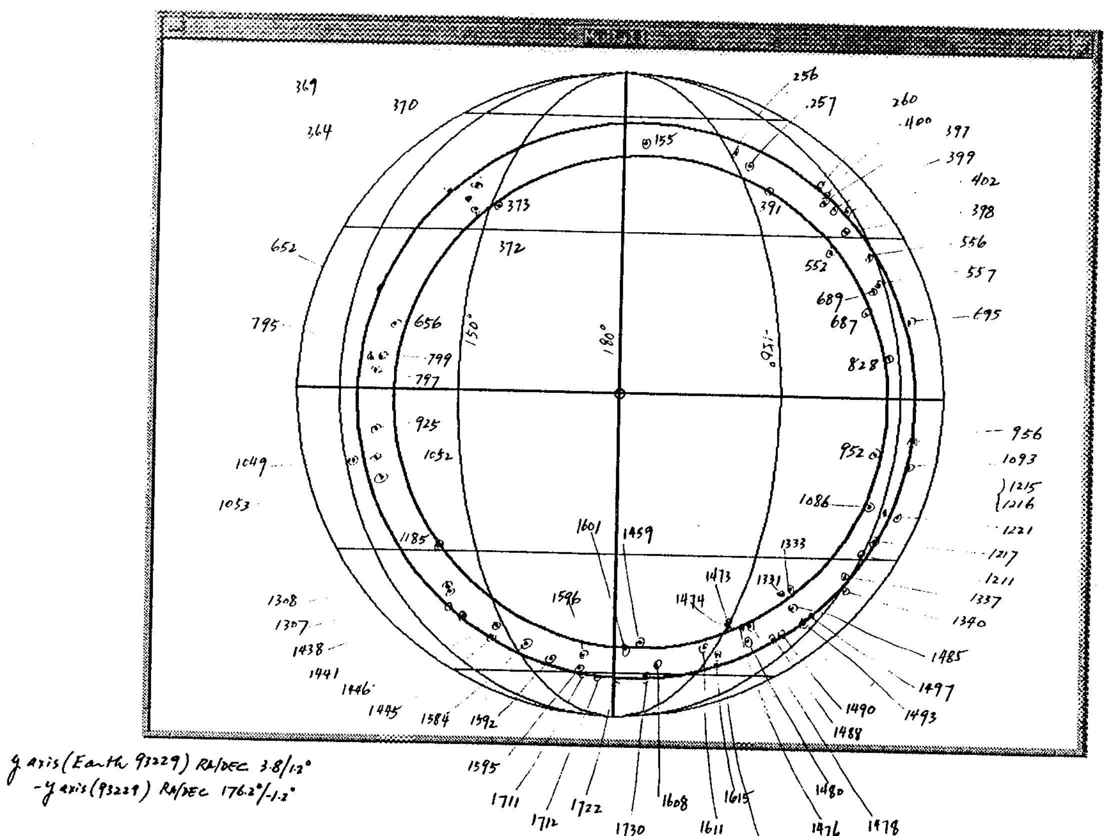

Figure 3. MOBALL Star Field Analysis - 93229 ANS Star Catalog