SHARP:
SPACECRAFT HEALTH
AUTOMATED REASONING PROTOTYPE

Presented by
David J. Atkinson

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

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OUTLINE

- BACKGROUND
- SHARP DESCRIPTION
- APPLICATIONS
- FUTURE DIRECTIONS
- BENEFITS, LESSONS LEARNED, CONCLUSIONS
PLANETARY SPACECRAFT MISSION OPS

• AGGRESSIVE PLANETARY EXPLORATION IN 1990's
  - MAGELLAN, GALILEO, ULYSSES, MARS OBSERVER, VOYAGER, CRAFT, CASSINI
  - POSSIBLE LUNAR AND MARS SPACECRAFT
  - ALL WILL BE FLYING AT THE SAME TIME
  - VOYAGER ALONE REQUIRED ABOUT 40 REAL-TIME OPERATORS AT ALL TIMES

• LARGE GROWTH IN MISSION OPERATIONS WORKFORCE, OPERATIONS COMPLEXITY... COSTS FORESEEN

• PROGRAM TO UPGRADE OPERATIONS INFORMATION SYSTEMS UNDERTAKEN: SPACE FLIGHT OPERATIONS CENTER, ONE MULTI-MISSION SPACE FLIGHT OPS TEAM

• GOALS: SUBSTANTIAL AUTOMATION, REDUCE WORKFORCE AND COST TO OPERATE, IMPROVE SAFETY, RELIABILITY, AND PRODUCTIVITY
SHARP TASK BACKGROUND

• "PROOF OF CAPABILITY" DEMONSTRATION TO EVALUATE BENEFITS OF AUTOMATION
  - PRODUCTIVITY OF MISSION OPERATIONS REAL-TIME ANALYSIS
  - SAFETY OF SPACECRAFT
  - RELIABILITY OF GROUND DATA SYSTEMS

• METHODOLOGY: ITERATIVE PROTOTYPING AND SPIRAL MODEL SOFTWARE DEVELOPMENT

• FIRST APPLICATION: VOYAGER TELECOMMUNICATIONS
# SHARP PROGRESS

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<th>Year</th>
<th>Event</th>
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<td>1987</td>
<td>Project Start</td>
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<tr>
<td>1989</td>
<td>SHARP for Voyager Telecom At Neptune</td>
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<tr>
<td>1990</td>
<td>SHARP Compatible with SFQC</td>
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<td>1991</td>
<td>SHARP for Magellan Telecom</td>
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<td>SHARP for Galileo Power and Pyro</td>
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<td>SHARP for DSN Link Monitor &amp; Control Pre-Cal</td>
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<tr>
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<td>Reusable Kernel</td>
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<tr>
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<td>Deeper Telecom Diagnosis</td>
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<td>1.5 Sec. to Diagnose</td>
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<td>&quot;Anytime&quot; Diagnosis</td>
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<tr>
<th>1991</th>
<th>Max ~ 100 RT Channels</th>
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<td>Max ~ 10K RT Channels</td>
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<td>Capacity to Spare</td>
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<td>Sun and SFQC Compatible</td>
<td>Installed in Magellan Ops</td>
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*Underway*
TELECOMMUNICATIONS OPERATIONS

• TELECOMMUNICATIONS LINK ANALYSIS:
  - MONITORING THE HEALTH AND STATUS OF THE TELECOMMUNICATIONS LINK BETWEEN THE SPACECRAFT, DEEP SPACE NETWORK, AND GROUND DATA SYSTEM COMPUTERS AT JPL

• MAJOR FUNCTIONS:
  - NUMERICAL ESTIMATION OF SYSTEM PERFORMANCE
  - MONITORING OF REAL-TIME ACTIVITY AND DETECTION OF FAILURES
  - DIAGNOSIS, ISOLATION, AND RECOVERY FROM FAILURES
TELECOMMUNICATIONS OPERATIONS

- CHARACTERISTICS:
  - MANUAL CALCULATIONS TO UPDATE & REVISE NUMERICAL PREDICTS
  - FREQUENTLY CHANGING HARDCOPY SEQUENCE OF EVENTS INFORMATION
  - MANUAL, LABORIOUS DETERMINATION OF ALARM LIMITS
  - VERY LIMITED COMPUTER DISPLAYS OF STATUS INFORMATION
  - ALL ALARM SITUATIONS ARE REFERRED TO EXPERT
  - TELECOM IS SUBJECT TO NUMEROUS ALARMS DAILY
SHARP DESCRIPTION

- FUNCTIONAL CAPABILITIES
  - MONITORING
  - DIAGNOSIS AND RECOVERY
  - DISPLAY AND USER INTERFACE
  - OTHER

- TECHNOLOGY
  - ROLE OF ARTIFICIAL INTELLIGENCE
  - EXAMPLE: ANOMALY DETECTION AND DIAGNOSIS

- APPLICATIONS PERFORMANCE
FUNCTIONAL CAPABILITIES

- FUNCTION OF THE SYSTEM: PROVIDE COMPUTER WORKSTATION SUPPORT FOR REAL-TIME SPACECRAFT SUBSYSTEM ANALYSTS

- CAPABILITIES INCLUDE:
  - REAL-TIME ANOMALY DETECTION, ANALYSIS AND DIAGNOSIS
  - DISPLAY MANAGEMENT, DATA VISUALIZATION AND SYSTEM STATUS
  - ACQUISITION AND CENTRALIZATION OF ENGINEERING DATA FOR ANALYSIS
  - INTEGRATION OF AI-BASED MONITORING AND DIAGNOSIS FUNCTIONS WITH CONVENTIONAL NUMERICAL ANALYSIS SOFTWARE
MONITORING

- CHANNELIZED DATA ON SERIAL OR NETWORK CONNECTIONS

- REAL-TIME PERFORMANCE WITH UP TO 10,000 CHANNELS EACH UPDATING 1/SEC

- AUTOMATED, CONTEXT SENSITIVE, ALARM LIMIT SELECTION

- DYNAMIC, DERIVED CHANNEL MONITORING

- EVENT SIGNATURE AND TREND MONITORING
DIAGNOSIS AND RECOVERY

- EXPLICIT CAPTURE OF EXPERT DIAGNOSTIC AND RECOVERY RULES AND PROCEDURES

- DOMAIN INDEPENDENT DIAGNOSTIC SHELL WITH DOMAIN-SPECIFIC DIAGNOSTIC KNOWLEDGE

- "ANYTIME" DIAGNOSIS -- REAL-TIME ANALYSIS USING BEST, TIME-SYNCHRONIZED DATA AVAILABLE

- DYNAMICALLY GENERATED HEALTH AND DIAGNOSTIC SUMMARIES OF SPACECRAFT SUBSYSTEMS

- RANKING OF UNCERTAIN HYPOTHESES FOR OPERATOR
DISPLAY AND USER INTERFACE

- SYSTEM STATUS DISPLAYS FROM MULTIPLE DATA SOURCES
  - REAL-TIME STATUS
  - PERFORMANCE OVER TIME

- GRAPHICAL VISUALIZATION AND DATA PLOTTING

- MIXED-INITIATIVE -- SYSTEM AND USER BOTH CONTROL THE DISPLAY
  - DISPLAY MANAGEMENT USING CONTEXT SENSITIVE MODELING OF FORMAT, CONTENT, SOURCE, AND RATIONALE

- DYNAMICALLY GENERATED USER HELP AND INPUT ERROR TOLERANCE
OTHER CAPABILITIES

- REAL TIME DATA CACHE AND ON-LINE HISTORICAL DATABASE

- EDITABLE ALARM PARAMETER AND EVENT DATABASES

- MONITORING AND DIAGNOSTIC CAPABILITIES EASILY INTEGRATED WITH CONVENTIONAL ANALYSIS ROUTINES (E.G., FAST FOURIER TRANSFORM)

- INTEGRATED WITH SPACE FLIGHT OPERATIONS CENTER (SFCC) DATA SERVICES
ROLE OF AI

- ARTIFICIAL INTELLIGENCE USED THROUGHOUT SHARP

EXAMPLES:

ARCHITECTURE: MULTI-PROCESS BLACKBOARD WITH OPPORTUNISTIC, DATA-DRIVEN CONTROL STRUCTURE

DATA HANDLING: HEURISTIC ADAPTIVE PARSING, TEMPORAL REASONING DECLARATIVE DATA REPRESENTATIONS

MONITORING: STATE MODELLING, DISCRIMINATION NETWORKS, TRUTH MAINTENANCE

DIAGNOSIS: HIERARCHICAL COMMUNICATING EXPERTS, REASONING IN MULTIPLE CONTEXTS

USER INTERFACE: RULE-BASED EXPERT SYSTEM TO MANAGE DISPLAYS, RULE-BASED DIAGNOSIS AND RECOVERY FROM INPUT ERRORS
ANOMALY DETECTION & DIAGNOSIS

• HIERARCHICAL SYSTEM BASED ON CLASSIFICATION PROCESS

• ALARM EXECUTIVE DETERMINES EXISTENCE OF ANOMALY BY COMPARING EXPECTED AND ACTUAL SPACECRAFT STATES
  - USE OF COMPILED DISCRIMINATION NETWORK TECHNIQUES
  - SOME FAILURES ARE UNIQUELY DETERMINED AT THIS STAGE

• FAULT CLASSIFICATION SUBSYSTEM
  - MAKES INITIAL CHARACTERIZATION OF THE PROBLEM
  - IDENTIFIES RELEVANT SOURCES OF DATA FOR USE IN DIAGNOSIS
  - APPROX. 60 RULES FOR VOYAGER TELECOM APPLICATION
  - POSTS INITIAL HYPOTHESES, DATA VALUES, SPACECRAFT STATE, OTHER INFO TO DIAGNOSTIC DATABASE
ANOMALY DETECTION & DIAGNOSIS

- SPECIALIZED "MINI-EXPERTS" FOR FAULT CLASSES
  - Triggered by fault hypotheses to reach detailed diagnosis and recovery recommendations
  - Pursue individual classes of faults (e.g., configuration errors) using specialized knowledge in the form of procedural networks
  - Operate independently in individual context trees

- Blackboard used to communicate and share results

- Hypothesis combination subsystem
  - Groups related conclusions and recommendations to operator, logs data, and signals modifications to operator's displays
APPLICATIONS PERFORMANCE

- ANOMALY DETECTION AND DIAGNOSIS
  - ABLE TO ANALYZE 39 CLASSES OF TELECOM PROBLEMS
  - 60 UNIQUE PROBLEM SOLVING DIAGNOSES
  - 20 ADDITIONAL DETECTABLE PROBLEMS
  - ABOUT 15 PROBLEMS ARE NOT COVERED
  - TOTAL FAULT COVERAGE IS ABOUT 80% AND IMPROVING AS KNOWLEDGE BASES ARE EXTENDED

- CONSCAN (ANTENNA POINTING) ERRORS DETECTED AND TRACKED BY SHARP UNTIL RESOLVED BY DSS OPERATORS

- (NON-CRITICAL) ANOMALIES DIAGNOSED BY SHARP
  - OPERATORS MANUALLY VERIFY THE DIAGNOSES
  - RCV AGC, S-BAND TWT BASE TEMP OCCURRED DURING VOYAGER ENCOUNTER
VOYAGER ENCOUNTER
SURPRISING EVENT

• RESOLVED VOYAGER SCIENCE DATA ERROR COMPLAINT PRIOR TO THE ENCOUNTER, AVOIDING A POTENTIAL CRITICAL SITUATION
  - SCIENCE PERSONNEL SAID CORRECTION COUNT WAS TOO HIGH
  - SHARP DETECTED AND REPORTED A POSSIBLE EXCESSIVE NOISE PROBLEM

• TELECOM PERSONNEL USED SHARP SCATTER PLOT OF BIT ERROR RATE VERSUS SYMBOL SIGNAL TO NOISE RATIO
  - CONFIRMED AN ANOMALOUS CONDITION WHICH WAS CORRUPTING THE SCIENCE DATA AT HIGH SSNR'S WHERE NO ERRORS ARE EXPECTED
  - DEFINED MAGNITUDE OF PROBLEM
  - PROVIDED ABILITY TO SHOW NO CORRELATION OF ERRORS WITH DSN STATIONS

• FURTHER INVESTIGATION TRACED PROBLEM TO A FAILED WIDE-BAND INTERFACE UNIT IN VGR DACS
  - SHARP USED TO CONFIRM PROBLEM RESOLUTION AFTER THE FAILED UNIT WAS REPLACED
DSN EXTENSIBLE GROUND ANALYSIS SYSTEM

- BACKGROUND
  - PLANNED FOR THE DSN'S NETWORK OPERATIONS CONTROL CENTER, WHICH MONITORS QUALITY OF NETWORK DATA AND STATUS OF ALL DSN SYSTEMS

- DSN EXTENSIBLE GROUND ANALYSIS SYSTEM (DEGAS)
  - SHARP-BASED ENHANCEMENT TO THE NOCC OPERATOR WORKSTATION

- KEY CHARACTERISTICS
  - VISUALIZATION OF CENTRAL NETWORK STATUS
  - RAPID ANOMALY DETECTION, DIAGNOSIS, AND RECOVERY.
  - EXTENSIBLE WITH EXTERNALLY DEVELOPED ANALYSIS MODULES.

- BENEFITS EXPECTED BY DSN
  - REDUCTION OF LARGE AMOUNTS OF DATA FOR PRESENTATION TO NOCT
  - ENABLE TIME-CRITICAL RESPONSE TO ANOMALIES
  - ASSIST IN OFF-LINE DIAGNOSIS, CALIBRATION, AND SYSTEM READINESS
DSN LINK MONITOR AND CONTROL OPERATOR ASSISTANT

• BACKGROUND
  - LMC OPERATORS AT DSN STATIONS CONFIGURE, CALIBRATE, AND CONTROL THE STATIONS ANTENNAS AND SUBSYSTEMS TO TRACK SPACECRAFT.
  - "PRE-CAL" OPERATIONS TAKE 45 MINUTES TO 4 HOURS TO COMPLETE

• LMC OPERATOR ASSISTANT
  - GOAL OF 30% REDUCTION IN TIME SPENT DURING PRE-CAL OPERATIONS
  - AUTOMATIC "DUAL CONTROL MODE", WHERE SINGLE OPERATOR CONFIGURES AND SYNCHRONIZES MULTIPLE ANTENNAS AND SUBSYSTEMS
  - AUTOMATIC PRE-CAL DIRECTIVE PLANNING AND PARAMETER SELECTION TO SHOW FEASIBILITY OF AUTOMATED CONTROL OF DSN STATION WITH OPERATOR ACKNOWLEDGEMENT.
    => BUT NO REAL DIRECTIVES FROM PROTOTYPE TO ACTUAL DSN SUBSYSTEMS
  - LAB DEMO IN 1991 FOLLOWED BY INSTALLATION AT GOLDSTONE DSS-13 FACILITY IN 1992
BENEFITS PROJECTED BY TELECOM USERS

• WORKFORCE SAVINGS
  Ultimate reduction in real time link analysis staff by a factor of five. Similar savings may be possible in other areas.

• SAFETY
  Real-time system can detect and analyze problems in seconds that take humans hours, e.g., antenna pointing errors.

• RELIABILITY
  System wide status monitoring helps assure correct system configuration, reduces commanding errors, and reduces loss of data.

• PRODUCTIVITY
  Reduced number of operations personnel can monitor a greater number of systems and perform required analyses more efficiently.
LESSONS LEARNED

- ENTHUSIASTIC PARTICIPATION OF END-USERS AND EXPERTS IS REQUIRED.
  - ENSURES ACCESS TO DOMAIN KNOWLEDGE AND FUTURE OPERABILITY.
  - PROVING "VALUE-ADDED" BY AUTOMATION IS DIFFICULT FOR TECHNOLOGISTS.

- PRACTICAL AUTOMATION USING AI REQUIRES EVOLUTION AND INTEGRATION WITH EXISTING SYSTEMS.
  - CONSTRAINTS OF EXISTING SYSTEMS LIMIT THE SCOPE OF THE AI APPLICATION.

- AI CANNOT BE APPLIED INDEPENDENTLY FROM OTHER TECHNOLOGIES (E.G., NETWORKING, GRAPHICS)
  - GOOD SYSTEM ENGINEERING IS WHAT MAKES A KNOWLEDGE SYSTEM.

- MAKE PRAGMATIC SELECTION OF MATURE AI TECHNIQUES
  - SUFFICIENT TOOLS ARE AVAILABLE BUT SKILLED DEVELOPERS ARE REQUIRED
CONCLUSIONS

- ARTIFICIAL INTELLIGENCE HAS A PROVEN CAPABILITY TO DELIVER USEFUL FUNCTIONS IN A REAL-TIME SPACE FLIGHT OPERATIONS ENVIRONMENT

- SHARP HAS PRECIPITATED MAJOR CHANGE IN ACCEPTANCE OF AUTOMATION AT JPL -- AI IS HERE TO STAY

- POTENTIAL PAYOFF FROM AUTOMATION USING AI IS SUBSTANTIAL

- SHARP, AND OTHER ARTIFICIAL INTELLIGENCE TECHNOLOGY IS BEING TRANSFERRED INTO SYSTEMS IN DEVELOPMENT
  - MISSION OPERATIONS AUTOMATION
  - SCIENCE DATA SYSTEMS
  - INFRASTRUCTURE APPLICATIONS