SSTAC/ARTS REVIEW OF THE DRAFT INTEGRATED TECHNOLOGY PLAN (ITP)

Volume VIII: June 26-27

Aerothermodynamics
Automation and Robotics (A&R) Systems
Sensors
High-Temperature Superconductivity

Briefings from the
June 24-28, 1991 Meeting
McLean, Virginia

National Aeronautics and Space Administration
Office of Aeronautics, Exploration and Technology
Washington, D.C. 20546
SSTAC/ARTS REVIEW OF THE DRAFT ITP
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High-Temperature Superconductivity

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FOR THE CIVIL SPACE PROGRAM

AEROTHERMODYNAMICS

AN ELEMENT OF THE
BASE RESEARCH AND TECHNOLOGY PROGRAM

JUNE 27, 1991

Jim Moss
Program Manager, Aerothermodynamics, Aerodynamics Division
Office Of Aeronautics, Exploration and Technology
National Aeronautics and Space Administration
Washington, D.C.

COMPARISON OF VEHICLE FLIGHT REGIMES IN
EARTH'S ATMOSPHERE
AEROTHERMODYNAMICS BASE R&T PROGRAM

AEROTHERMODYNAMICS

• It is the process of developing and applying analytical and experimental capabilities to understand the complex, hypervelocity flow environment in which a particular vehicle must operate.

• It is also the conduct of analytical and experimental research to advance the technology of aerothermodynamically efficient vehicle design.

BENEFITS

• DEFINITION OF FLIGHT ENVIRONMENT FOR VEHICLE DESIGN CRITERIA
  - FLIGHT CONTROLS, STRUCTURES, MATERIALS/TPS, PROPULSION, ETC.

• MORE OPTIMIZED OVERALL PERFORMANCE (COST)
AEROTHERMODYNAMICS BASE R&T PROGRAM

PAYOFF EXAMPLES

TRANSPORTATION: AEROTHERMODYNAMICALLY EFFICIENT CONFIGURATION DESIGN RESULTS IN:

• IMPROVED DESIGN MARGINS
  - FLIGHT ENVIRONMENT DEFINITION REDUCES TPS UNCERTAINTY (+2000 LB NSTS)
  - AERODYNAMIC PERFORMANCE INCREASES CONTROL AUTHORITY (ORBITER ENTRY CM ANOMALY)
  - AEROLEADS DEFINITION INCREASES LAUNCH FLEXIBILITY ($10+M PER FLIGHT)
  - AEROHEATING DEFINITION INCREASES CROSS RANGE (+300+MILES NSTS)
• REUSABILITY INCREASES OPERATIONAL EFFICIENCY ($100+M PER FLIGHT)
• AERODYNAMICS INCREASES FLYING QUALITIES (BETTER FLYABILITY AND REDUCED PROFICIENCY TRAINING)

AEROTHERMODYNAMICS BASE R&T PROGRAM

PAYOFF EXAMPLES (CONT.)

EXPLORATION: AEROTHERMODYNAMIC CAPABILITIES ENABLE EXPLORATION MISSIONS:

• AEROBRAKING VS. ALL-CHEMICAL PROPULSION RESULTS IN 30-40% REDUCTION IN LEO MASS AND INCREASED PAYLOAD RETURN (1000'S LBS)
• AEROMANEUVERING (L/D) IMPROVES CROSS RANGE (UP TO MARS GLOBAL COVERAGE)
• ATMOSPHERE BRAKING ENHANCES PLANETARY SCIENCE (ATMOSPHERE STRUCTURE AND COMPOSITION)
AEROTHERMODYNAMICS BASE R&T PROGRAM

SPACE TRANSPORTATION ARCHITECTURE OPTIONS


SPACE SHUTTLE

SPACE STATION FREEDOM

ACRV (assured return)

PLS (assured return)

NLS (Multi-role Heavy-lift)

AMLS

SEI

AEROTHERMODYNAMICS BASE R&T PROGRAM

INVOLVES THE FULL INTEGRATION OF THREE ESSENTIAL, UNIQUE CAPABILITIES TO PROVIDE THE DESIGN CRITERIA FOR FUTURE VEHICLES

Conceptual design and analysis

Prediction

Verification

Computational Tools

Experimental analysis (ground and flight)

Code validation
AEROTHERMODYNAMICS BASE R&T PROGRAM

MUTUALLY DEPENDENT TECHNOLOGIES

- Data beyond capability of ground facilities
- Test in actual flight environment
- Critical problem identification
- Validate portions of Computational Tools
- Parametric studies
- Detail study of phenomena
- Interpret ground and flight tests
- Data base expansion
- Specific design integration
- Explore single and multi-parameter variations

AEROTHERMODYNAMICS BASE R&T PROGRAM

AUGMENTATION PLAN

CAPABILITY DEVELOPMENT

- COMPUTATIONAL TOOL DEVELOPMENT
- EXPERIMENTAL RESEARCH/COMPUTATIONAL VALIDATION
- FACILITIES RESEARCH

CAPABILITY APPLICATION

- CONFIGURATION ASSESSMENT
AEROTHERMODYNAMICS BASE R&T PROGRAM
BUDGET IMPLICATIONS

RUNOUT OF AUGMENTED (STRATEGIC) PROGRAM ($M)

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AE1-6
AEROTHERMODYNAMICS BASE R&T PROGRAM
RUNOUT OF AUGMENTED (STRATEGIC) PROGRAM ($M)

- Facilities Operations
- Generic Hypersonics
- Configuration Assessment
- Facilities Research/Development
- Experimental Research/Computational Validation
- Computational Tool Development

FISCAL YEAR

FY 92 FY 93 FY 94 FY 95 FY 96 FY 97

$M
50 45 40 35 30 25 20 15 10 5

COMPUTATIONAL TOOL DEVELOPMENT

AE1-7
AEROTHERMODYNAMICS
COMPUTATIONAL TOOL DEVELOPMENT

DETAILED FLOWFIELD/FLUID PROPERTIES ANALYSIS TOOLS
TECHNOLOGY NEEDS

COMPUTATIONALLY EFFICIENT,
ACCURATE PREDICTION OF AERODYNAMICS,
ACCURATE HIGH TEMPERATURE GAS PROPERTIES,
HEAT TRANSFER FOR 3-D CONFIGURATIONS IN REAL-GAS FLIGHT ENVIRONMENT,
ACCURATE, INTEGRATED ANALYSIS FOR DEFINING LOCAL AEROTHERMAL LOADS CRITICAL
TO MATERIAL AND STRUCTURAL CONCEPT SELECTION

CURRENT PROGRAM S-O-A

3-D CONFIGURATIONS, EQUILIBRIUM GAS COMPUTATIONS "IN-HAND"; THERMOCHEMICAL,
NON-EQ SOLUTIONS AND DSMC TECHNIQUES NOT VALIDATED; PHYSICAL PROCESS MODELING
REQUIRES EXTENSIVE IMPROVEMENTS; COMPUTATIONAL TIME REQUIREMENTS
EXTREME FOR 3-D

AUGMENTED PROGRAM

MORE EFFICIENT COMPUTATIONAL ALGORITHMS DEVELOPED;
BROADER RANGE OF PHYSICAL PROCESS MODELS WITH REDUCED LEVELS
OF UNCERTAINTY (RADIATIVE TRANSPORT, THERMOCHEMICAL KINETIC RATES,
TURBULENCE); MORE AGGRESSIVE ROLE IN DESIGNING EXPERIMENTS

AE1-8
AEROTHERMODYNAMIC CFD CODE DEVELOPMENT

FREE MOLECULAR FLOW

DIRECT SIMULATION MONTE CARLO

BURNETT

AEROTHERMODYNAMICS BASE R&T PROGRAM

Low Density Flow Regimes

- "LOW DENSITY EFFECTS" ARE A FUNCTION OF THE LOCAL LENGTH SCALE AND THE LOCAL MEAN FREE PATH LENGTH (LOCAL KNUDSEN NUMBER, Kn = \lambda/L)
- THEY ARE NOT JUST A HIGH ALTITUDE PHENOMENA

AE1-9
DSMC SIMULATION OF FLOW ABOUT SHUTTLE ORBITER

Alt = 120 km

Alt = 100 km

Alt = 170 km

BLUE = Molecules unaffected by vehicle
RED = Molecules that have struck the surface
YELLOW = Blue in collision with red or yellow

Stagnation Line Profiles of the ARE

Temperature (K)
Distance (cm)

WJF 6/11/91 (18)

AE1-10
Streamlines Near Shock-Shock Interaction

(preliminary results)

Cowl Surface

High Altitude Hypersonic Flow about an ASTV
Knudsen Number Comparisons

Navyer Stokes: Augmented Burnett

F. Lumpkin & E. Venkatapathy
AFE SURFACE HEATING

\[ V = 9.3 \text{ km/s} \quad h = 75 \text{ km} \quad \alpha = -5^\circ \]

WAKE FLOWS FOR AEROBRAKES
SHEAR-LAYER DEFLECTION ANGLES

Provides Estimate Of
Shear-layer Location
For Aft Payload Packaging

Ground-based Experimental Data
- AFE
- Blunt Bodies

Computations, Flight Conditions
- AFE
- Lunar

\[ \theta, \text{ deg} \]

\[ \alpha, \text{ deg} \]
ADVANCEMENT IN RADIATIVE TRANSPORT
AFE Equivalent Sphere Radiative Flux

Modified Differential Approximation (MDA) Shows Potential For Solving 3-D Radiative Transport

COMPARISON OF THREE CHEMICAL REACTION RATE SETS

\( V_\infty = 12 \text{ km/sec}, \text{ altitude} = 80 \text{ km}, R_{\text{nose}} = 1.08 \text{ m} \)

Kang and Dunn
Park (87)
Park (91)

Stagnation Line Electron Number Density

Surface Heating
Initial Shuttle Surface and Volume Grid

SHUTTLE ORBITER PRESSURE
Mach = 7.4, $\alpha = 40^\circ$

Flowfield and Surface Pressure

Centerline Surface Pressure

AE1-14
FLOW TEMPERATURE

AFE Afterbody

Adapted grid based on density, pressure and temperature gradients

Temperature contours obtained using adopted grid showing recompression shock and shear layer
STAGNATION POINT HEATING RATE ON AFE

$T_w = 1765^\circ K$, Reuseable Tile Slumping Starts and Thermocouple Temperature Limit Reached

- Radiative Heating
- VSL - Without Slip
- NS - Without Slip
- NS - With Slip

Results Used to Define Correction Factors in Design Methodology

Windward Symmetry Plane Heating Distribution

Heating Contours on Modified Shuttle Orbiter

Circumferential Heating Distribution

Heating Distribution Along Leading Edge

AE1-16
VEHICLE SYNTHESIS ENGINEERING TOOLS

TECHNOLOGY NEEDS

ROBUST AND RAPID AERODYNAMIC AND AEROTHERMODYNAMIC
ENGINEERING METHODS FOR CONFIGURATIONAL DESIGN AND OPTIMIZATION

CURRENT PROGRAM S-O-A

"APAS" - AERODYNAMIC PRELIMINARY ANALYSIS SYSTEM - ENGINEERING CODE
DEVELOPED WITH CAPABILITIES TO PREDICT VEHICLE AERO/HEATING.
REQUIRES IMPROVEMENTS IN MODELING FOR TRANSONIC REGIME AND
HEATING IN HYPersonic REGIME

AUGMENTED PROGRAM

"APAS" TO RAPIDLY PREDICT TOTAL FORCES, MOMENTS, CONTROL EFFECTIVENESS,
AND HEATING OF COMPLETELY ARBITRARY CONFIGURATIONS THROUGHOUT
EXPECTED FLIGHT REGIME FOR USE IN DESIGN AND OPTIMIZATION.
ENHANCED SOLID MODELING AND INCORPORATION OF
EXPERT SYSTEMS AND ADVANCED OPTIMIZATION
ALGORITHMS
AEROTHERMODYNAMICS
COMPUTATIONAL TOOL DEVELOPMENT

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AEROTHERMODYNAMICS BASE R&T PROGRAM

EXPERIMENTAL RESEARCH/COMPUTATIONAL VALIDATION
GROUND-BASED DATA ACQUISITION AND ANALYSIS

TECHNOLOGY NEEDS

FUNDAMENTAL FLUID PHYSICS AND CODE VALIDATION DATABASES:
THERMOCHEMICAL NONEQUILIBRIUM, RADIATION, VISCOS DOMINATED FLOWS,
SEPARATED FLOWS, GAS-SURFACE INTERACTIONS, TRANSITION/TURBULENCE,
WAKE STRUCTURE, PLUME-SURFACE INTERACTIONS

CURRENT PROGRAM S-O-A

CERTAIN HYPERSONIC SIMILITUDE PARAMETERS MAY BE REPLICAED WITH WIND
TUNNELS OVER LIMITED RANGES OF VALUES WITH ACCURATE MEASUREMENTS FOR ONLY
GROSS FLOWFIELD AND POINTWISE SURFACE PROPERTIES. REAL GAS
FACILITIES EXPAND THE PARAMETER RANGE, BUT LIMITED
IN SIZE, FLOW QUALITY, AND FLOW DIAGNOSTICS

AUGMENTED PROGRAM

DATABASES THAT ENCOMPASE A BROADER SPECTRUM OF FLUID PHYSICS FOR
UTILIZATION OF EXISTING HIGH ENTHALPY FACILITIES, INCREASED
TESTING IN UNIQUE, COMPLEMENTARY, NON-NASA FACILITIES
MORE AGGRESSIVE INVOLVEMENT OF CFD IN
EXPERIMENT DEFINITION

ADVANCES IN COMPUTATIONAL CAPABILITY

(Mach 10 Air, \( \alpha = -5^\circ \), \( Re_L = 159,000 \))

Surface Grid

- \( s \) = Arc Length in Symmetry Plane Measured from Stagnation Point
- \( L \) = Base Diameter (3.67 in.)
- \( C_P \) = Pressure Coefficient
- \( C_H \) = Heat Transfer Coefficient Referenced to Fay and Riddell Stagnation Point Value

\( C_H \) and \( C_P \) vs. (s/L)

LAURA
Experimental
HYPersonic Rarefied Flow About a Delta Wing: Comparison of DSMC and Experiment

Delta Wing Model

Density Contours
Kn = 0.016

Heat Transfer

Lift Coefficient

TWA
National Aeronautics and Space Administration
$35^\circ$ Ramp, $\rho_\infty = 39.12 \times 10^{-5}$

$M_\infty = 21.58$, $\lambda_\infty = 0.073$ mm, $T_w = 341$ K

DENSITY ($\rho/\rho_\infty$)

SKIN FRICTION

STREAMLINES

MACH NUMBER

COMPARISON OF EXPERIMENTAL AND SIMULATED RESULTS FOR INCipient SEPARATION

Incipient Separation Correlation: $\beta_i = 80 \sqrt{V'}$
ELECTRIC ARC-DRIVEN SHOCK TUBE FACILITY

PERFORMANCE OF ELECTRIC ARC DRIVEN SHOCK TUBES
AT NASA AMES RESEARCH CENTER

DRIVER GAS DRIVER GAS DRIVER GAS DRIVER GAS
A 4 Ne AIR 30 m 0 4 Ne AIR CONICAL
B 24 Ne AIR 30 m O 24 Ne AIR CONICAL
C 4 H2 H2 54 m O 4 Ne AIR CONICAL
D 4 He Ar 54 m 0 4 Ne CO2 CONICAL
E 4 He H2/Ne 54 m 0 4 Ne AIR 54 m

PRESSURE, P_0 [bar]

SHOCK VELOCITY, U_s [km/sec]
Ames 10 cm Shock Tube Nozzle Flow
Translational and Vibrational Temp.
\( T_1 = 7157 \text{ K}, \ p_1 = 1493 \text{ psi}, \ \alpha = 4.7 \times 10^3 \text{ cm}^{-1} \)
Figure 9. Comparison of theory and experiment, rotational temperature

Figure 10. Comparison of theory and experiment, vibrational temperature
FLIGHT DATA ANALYSIS

TECHNOLOGY NEEDS

FLIGHT DATA ANALYSIS LEADING TO IMPROVED GROUND-TO-FLIGHT DATA EXTRAPOLATION TECHNIQUES, AND VALIDATED AEROTHERMODYNAMIC SIMULATION CAPABILITIES

CURRENT PROGRAM S-O-A

LOW LEVEL-OF-EFFORT, IN-HOUSE RESEARCH ANALYSIS OF OEX DATA

AUGMENTED PROGRAM

SIGNIFICANTLY INCREASED LEVEL-OF-EFFORT TO INCLUDE ANALYSIS OF OEX (EARTH-TO-ORBIT), AFE (AEROBRAKING), GALILEO (PLANETARY ENTRY) DATA

TYPICAL SILTS QUANTITATIVE DATA - STS-28

Altitude = 216 kft
Mach Number = 19.8
Angle-of-Attack = 39.5 deg

Temp (°F)

1100
1000
900
800
700
600
500
400
CSE EXPERIMENT CONFIRMS NON-CATALYTIC BENEFIT OF GLASS TILE COATING IN FLIGHT ENVIRONMENT

- ○ RCG Coating (Baseline)
- ● Catalytic Overcoat

STS-2
Mach 23.4
Altitude = 233 kft

Equilibrium Chemistry Prediction

\[ \dot{q} = \frac{\text{Btu}}{\text{ft}^2\text{sec}} \]

\[ \text{x/L} \]

AE1-27
SHUTTLE ACCELEROMETRY (HiRAP/IMU) DENSITY MEASUREMENTS

HiRAP PROVIDES VALIDATION DATA FOR RAREFIED FLOW COMPUTATIONAL TOOLS

Free Molecule Limit (Diffuse)
335-kg GALILEO ENTRY PROBE

- $R_B = 0.632$ m
- $R_n = 0.222$ m
- $\theta = 44.86^\circ$
- AEROSHELL
- BOND
- 30° TAPE-WRAPPED CARBON PHENOLIC
- CHOPPED-MOLDED CARBON PHENOLIC

FOREBODY FLOW PHENOMENA—JUPITER ENTRY

- $T = 16000$ K
- $R_N = 0.311$ m
- $U_{\infty} = 39.29$ km/sec
- $\rho_{\infty} = 4.36 \times 10^{-4}$ kg/m$^3$
- $T_{\infty} = 151$ K
- $T = 12000$ K
- $T = 13000$ K
- $T_w \approx 4000$ K
- $P_w \approx 6 - 3$ atm
- INVISCID HYDROGEN-HELIUM GASES
- TURBULENT LAYER WITH ABLATION SPECIES
- CHEMICAL NONEQUILIBRIUM
- RADIATION
- ABLATION INJECTION (CARBON + OXYGEN + HYDROGEN)
DSMC PROVIDES DEFINITION OF AFE RAREFIED FLOW AERODYNAMIC PERFORMANCE

![Graph showing 3-D DSMC Results, α = 17°, C_L, C_D, Analytical Bridging Formula](image)

AE1:30
AEROTHERMODYNAMICS BASE R&T PROGRAM

EXPERIMENTAL RESEARCH/COMPUTATIONAL VALIDATION

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GROUND-BASED DATA ACQUISITION AND ANALYSIS

- Complete Nonequilibrium Air Radiation Database
- Thermal Nonequilibrium Data for Free Jet
- Thermochemical Nonequilibrium Reactions and Radiation (Expanding $\text{CO}_2/\text{H}_2$)
- Aerodynamic Database for Mars Aerocapture/Entry

FLIGHT DATA ANALYSIS

- Complete OARE Analysis
- Initiate Analysis of Galileo Data
- Initiate Analysis of APE Data

AEROTHERMODYNAMICS BASE R&T PROGRAM

FACILITIES

RESEARCH/DEVELOPMENT
# AMES FACILITIES

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# CHARACTERISTICS OF LaRC HYPERSONIC FACILITIES COMPLEX

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<th>$T_0$, °R</th>
<th>$M_\infty$</th>
<th>$R_{\infty}/ft$ x 10^6</th>
<th>$p_2/p_\infty$</th>
<th>Nozzle Type</th>
<th>Nozzle Exit, in.</th>
<th>Test Core, in.</th>
<th>Run Time, sec</th>
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</thead>
<tbody>
<tr>
<td>20-In. M6 CF₄</td>
<td>CF₄</td>
<td>100-2500</td>
<td>1100-1460</td>
<td>6</td>
<td>0.03-0.7</td>
<td>12.0</td>
<td>Axis.</td>
<td>20 D.</td>
<td>14</td>
<td>10-30</td>
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<td>20-In. M6</td>
<td>Air</td>
<td>30-500</td>
<td>760-960</td>
<td>6</td>
<td>0.5-9</td>
<td>5.3</td>
<td>2D</td>
<td>20x20</td>
<td>12x12-14x14</td>
<td>120-900</td>
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<td>15-In. M6 Hi T</td>
<td>Air</td>
<td>50-250</td>
<td>1100-1500</td>
<td>6</td>
<td>0.5-4</td>
<td>5.3</td>
<td>Axis.</td>
<td>15 D.</td>
<td>8-10</td>
<td>120</td>
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<tr>
<td>12-In. M6 P</td>
<td>Air</td>
<td>50-2700</td>
<td>700-1060</td>
<td>6</td>
<td>1-40</td>
<td>5.3</td>
<td>Axis.</td>
<td>12 D.</td>
<td>4-8</td>
<td>180 to vacuum 900 to atm</td>
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<tr>
<td>18-In. M8</td>
<td>Air</td>
<td>30-3000</td>
<td>1160-1500</td>
<td>7.5-8.0</td>
<td>0.1-12</td>
<td>5.6</td>
<td>Axis.</td>
<td>18 D.</td>
<td>7-16</td>
<td>90 to vacuum 600 to atm</td>
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<tr>
<td>31-In. M10</td>
<td>Air</td>
<td>125-1450</td>
<td>1830</td>
<td>10</td>
<td>0.25-2</td>
<td>6.0</td>
<td>3D</td>
<td>31x31</td>
<td>12x12-14x14</td>
<td>60</td>
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<tr>
<td>20-In. M17 N₂</td>
<td>N₂</td>
<td>2000-5500</td>
<td>2800-3500</td>
<td>17</td>
<td>0.2-0.8</td>
<td>6.6</td>
<td>Axis.</td>
<td>20 D.</td>
<td>8-10</td>
<td>3600</td>
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<tr>
<td>60-In. M18 He</td>
<td>He</td>
<td>300-2000</td>
<td>520-18.5</td>
<td>2-15</td>
<td>4</td>
<td>Axis.</td>
<td>60 D.</td>
<td>20</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>22-In. M20 He</td>
<td>He</td>
<td>300-3000</td>
<td>520-18.5</td>
<td>2-15</td>
<td>4</td>
<td>Axis.</td>
<td>60 D.</td>
<td>20</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

*Note: The table contains data on various test conditions and parameters for different facilities. The data includes gas type, pressure, temperature, Mach number, and other relevant details.*
AEROTHERMODYNAMICS
FACILITIES RESEARCH/DEVELOPMENT

EXISTING FACILITY UPGRADES

TECHNOLOGY NEEDS

HIGH FLOW QUALITY, EXPANDED SIMULATION BOUNDARIES, INCREASED OPERATIONS EFFICIENCY AND PRODUCTIVITY

CURRENT PROGRAM S-O-A

UTILIZING OLD FACILITIES THAT PROVIDE SIGNIFICANT RANGE OF SIMULATION PARAMETERS; TUNNELS HAVE LIMITED VACUUM CAPABILITY AND MODEL OPTICAL ACCESS; SOME UPGRADES MINOR/MAJOR CoF AND R&D (LaRC HFC, EAST, AND 16" SHOCK TUNNEL); BALLISTIC RANGE BARELY OPERATIONAL, RADIATION RANGE DEACTIVATED, ARC JETS NOT SUITABLE FOR AERO/AEROTHERMODYNAMIC TESTING

AUGMENTED PROGRAM

EXPANDED SIMULATION CAPABILITY (NOZZLES, HEATERS, VACUUM SYSTEMS, DIFFUSERS, AFTER COOLERS, PUMP/LAUNCH TUBE, SHOCK TUBES), IMPROVED FLOW QUALITY (NOZZLES, IN-LINE FILTERS, AUTOMATED PRECISION FLOW CONTROL), UPGRADED DATA ACQUISITION, REACTIVATED RADIATION FACILITY
AEROTHERMODYNAMICS BASE R&T PROGRAM

Shock Wave Generation Capabilities
for Shock Structure Studies

SIMULATING CAPABILITIES FOR 1/100 SCALE MODEL
SIMULATING ENTHALPY, MACH, AND REYNOLDS NUMBERS

AE1-35
AEROTHERMODYNAMICS
FACILITIES RESEARCH/DEVELOPMENT

TEST TECHNIQUE DEVELOPMENT

TECHNOLOGY NEEDS

GLOBAL QUANTITATIVE SURFACE MEASUREMENTS, BENCHMARK DISCRETE SURFACE MEASUREMENTS, NON INTRUSIVE DIAGNOSTICS (FLOWFIELD STATE/RADIATION), TECHNIQUES TO CHARACTERIZE HYPERSONIC TURBULENT FLOWS, 3-D FLOW VISUALIZATION METHODS, DEVELOPMENT OF FLIGHT QUALIFIED TEST INSTRUMENTS

CURRENT PROGRAM S-O-A

REFINEMENT OF GLOBAL SURFACE TEMPERATURE MEASUREMENTS, LIMITED APPLICATION OF NONINTRUSIVE MEASUREMENT TECHNIQUES (SCATTERING AND LASER VELOCIMETRY IN MACH 6 AIR AND 3.5'; OMA EMISSION SPECTRA, RAMAN SCATTERING, AND LHI IN EAST FACILITY; SCANNING LASER ABSORPTION AND LHI IN 16" SHOCK TUNNEL), LIMITED APPLICATION OF INTRUSIVE MEASUREMENT TECHNIQUES, ANTIQUATED/LIMITED FAST RESPONSE MEASUREMENT CAPABILITY

AUGMENTED PROGRAM

GLOBAL SURFACE QUANTITIES (REFINE THERMOMETRIC, DEVELOP PRESSURE), DEVELOPMENT/IMPLEMENTATION OF NONINTRUSIVE MEASUREMENT TECHNIQUES (PLIF, RAYLEIGH/RAMAN SCATTERING, LHI, OMA EMISSION SPECTRA, CARS, E-BEAM, LDV, NO AND O2 LASER TOMOGRAPHIC), DEVELOP FLOW VISUALIZATION SYSTEMS WITH VIDEO RECORDING AND IMAGE ENHANCEMENT, OBTAIN FAST RESPONSE INSTRUMENTATION

PHOSPHOR THERMOGRAPHY ACQUISITION SYSTEM

- Wind Tunnel
- UV Lamps
- Phosphor Emission
- Camera
- Image Processor
- External Trigger Circuit
- PC Controller (Compaq 386 20)
- Image Hardcopy
- Large Screen Monitor
APPLICATION OF THERMOGRAPHIC PHOSPHOR TECHNIQUE

CENTERLINE (y = 0)
- Thermographic phosphor
- Films

GLOBAL HEATING RATES IMMEDIATELY FOLLOWING TEST

AEROTHERMODYNAMICS FACILITIES RESEARCH/DEVELOPMENT

FACILITIES CONCEPT STUDIES

TECHNOLOGY NEEDS

TECHNOLOGY MATURATION FOR HYPERVELOCITY, FREE-FLIGHT/TRACK FACILITY (AHAF) (LAUNCHERS, ON BOARD INSTRUMENTATION, MODEL/SABOT INTEGRATION, ASYMMETRIC AND/OR ANGLE OF INCIDENCE TESTING, CONTAINMENT/RECOVERY); IMPROVED ARC JET FLOWS FOR AEROTHERMODYNAMIC TESTING, LOW DENSITY WIND TUNNEL

CURRENT PROGRAM S-O-A

MODEST EFFORT SUPPORTING TECHNOLOGY MATURATION FOR AHAF (HEAVILY DEPENDENT ON DOD, DARPA, AND SDIO FUNDING), ANALYTICAL STUDIES OF IMPROVED ARC JET FACILITIES

AUGMENTED PROGRAM

ACCELERATED DEVELOPMENT OF AHAF TECHNOLOGIES, DOCUMENTED ARC JET FLOWFIELDS, IMPROVED DESIGN OF ARC HEATERS AND TUNNELS, PILOT FACILITY DEVELOPMENT, A LOW DENSITY WIND TUNNEL

COPY IS OF POOR QUALITY
WHAT IS DIFFERENT ABOUT ADVANCED HYPERVELOCITY AEROPHYSICS FACILITY (AHAF)?

- In one word - SIZE

- Near order of magnitude increased in model size provides:
  - Testing of full-size vehicle components (e.g. nose tips)
  - Volume for large amounts of onboard instrumentation
  - Aerodynamic forces and moments
  - Detailed pressure and heat transfer distributions for analysis of aerodynamic and aerothermal loads

- Sufficient shock/boundary layer thickness for:
  - Determination of scaling (finite rate chemistry) effects
  - Measurement of flowfield properties via offboard advanced diagnostics

- Etc. (reference workshop proceedings NASA CP 10031)
COMPARISON OF VEHICLE FLIGHT REGIMES IN EARTH'S ATMOSPHERE

Aeroassist flight experiment
Low-lift AOTV
Coplanar GEO → LEO

High-lift AOTV (45° LEO plane change)
Mars return
Proposed facility
Launch tube
Dia., in.-18.0
Launch tube
Dia., in.
"G" 2.5
1.5

Altitude x 10^-3, ft

Velocity X 10^-3, ft/sec (approximate Mach number)

Concorde
Hypersonic transport

0 10 20 30 40 50

2 in. dia. current
12 in dia. AHAF

36 in.
-6 in.
ADVANTAGES OF THE RANGE CONCEPT

- Correct velocity and density - energy modes in gas correct
- No support/sting interference - base flow effects
- Quiescent test medium - boundary layer transition
- Species distribution and magnitude
- Chemistry effects modeled where binary scaling is valid
- Gas/surface interactions
- Spatial resolution of surface effects flowfield properties
- Validation of CFD codes
- Spatial and spectral distribution of radiation data

AEROTHERMODYNAMICS BASE R&T PROGRAM

FACILITIES RESEARCH/DEVELOPMENT

<table>
<thead>
<tr>
<th>FY 93</th>
<th>FY 94</th>
<th>FY 95</th>
<th>FY 96</th>
<th>FY 97</th>
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<tbody>
<tr>
<td><img src="image1" alt="Existing Facility Upgrades" /></td>
<td><img src="image2" alt="Existing Facility Upgrades" /></td>
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<td><img src="image4" alt="Existing Facility Upgrades" /></td>
<td><img src="image5" alt="Existing Facility Upgrades" /></td>
</tr>
</tbody>
</table>

EXISTING FACILITY UPGRADES

- 16" Shock Tunnel
- 19" Mach 6
- EAST
- 20" Mach 6
- 20" Mach 17 N₂
- Ballistic Range

TEST TECHNIQUE DEVELOPMENT

- LIF and LHI in Shock Tubes
- 3-D Raman/Rayleigh Scattering Diagnostics in HWT
- Emission and Absorption Spectra in Shock Tubes
- E-Beam in Mach 17 H₂ and HYPULSE
- CARS in EAST
- Laser Tomography in 16"

TEST TECHNIQUE DEVELOPMENT

- AHAF Concept Definition
- RFF pre PER
- Launcher Study Completed
- AHAF pre PER
- RFF pre PER
- Rarefied Flow Facility Operational
- Rarefied Flow Facility Designed

AE1-40
AEROTHERMODYNAMICS BASE R&T PROGRAM

CONFIGURATION ASSESSMENT

TECHNOLOGY NEEDS

CREDIBLE EARLY PHASE VEHICLE DEVELOPMENT; VERIFICATION OF PERFORMANCE; CAPABILITY TO SUPPORT USER REQUIREMENTS; OPTIMIZED CONFIGURATIONS; ENHANCED DATA BASE; KNOW HOW TO CORRECT DEFICIENCIES

CURRENT PROGRAM S-O-A

LIMITED RESOURCES — 1 - 2 VEHICLES AT A TIME
FOCUS ON ONE PLS CONCEPT AND AFE

AUGMENTED PROGRAM

MODELS, COMPUTER TIME, AND FACILITY OPERATIONS TO ASSESS:

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>ACRV</td>
<td>(4 - 8)</td>
<td>SDIO-SSTO</td>
<td>(1 - 2)</td>
</tr>
<tr>
<td>PLS</td>
<td>(3)</td>
<td>NLS</td>
<td>(TBD)</td>
</tr>
<tr>
<td>AMLS</td>
<td>(Unlimited)</td>
<td>NDV</td>
<td>(TBD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OTHER</td>
<td>(TBD)</td>
</tr>
</tbody>
</table>

AE1-41
AEROTHERMODYNAMICS BASE R&T PROGRAM

SPACE TRANSPORTATION ARCHITECTURE OPTIONS


SPACE SHUTTLE

SPACE STATION FREEDOM

ACRV (assured return)

PLS (assured return)

NLS (Multi-role Heavy-lift)

AMLS

SEI

SPACE TRANSPORTATION ARCHITECTURE SYSTEMS

Space Shuttle

PLS

NLS Core

NLS HEAVY LIFT

Core+strapons

AMLS

SSTO

AE1-42
AE-20 LONGITUDINAL CHARACTERISTICS
(Moment ref = 0.54L)

LOW SPEED

TRANSONIC
$\delta_e = 0^\circ$

HYPersonic
$\delta_e = 0^\circ$

L/D

$\delta_e$, deg
- O -10
- □ 0
- ▲ 10

$C_m$

Mach no.
- O 20.0
- □ 4.6
- ▲ 3.6

$\alpha$, deg

0 10 20 30 40

0 10 20 30 40

-0.08 -0.04 0 0.04 0.08

-0.08 -0.04 0 0.04 0.08

AEI-43
SUBSONIC L/D ENHANCEMENT FOR HL-20/HL-20A

CHARACTERISTICS

α = 30°

- HL-10 (M=8)
- PLS lifting body (M=6)
- Shuttle (M=6)
MACH NUMBER CONTOUR PLOTS

\[ M_\infty = 10 \quad \alpha = 25^\circ \quad \gamma = 1.4 \]

DSMC SIMULATION OF FLOW ABOUT PLS/ACRC

Alt = 100 km, \( V_\infty = 7.5 \text{ km/sec}, \alpha = 20^\circ \)
Entry from Orbit 1 into KSC
Transition $R_e_0 / M_e = 335$

Peak heat rate, Btu/ft²-sec

Peak radiation equilibrium temperature, °F

ACC nosecap (3000°F)

HRSI (2500°F)

Rad. eq. temp.

Heat rate

x location, ft
AEROASSIST VEHICLE DESIGN CHOICES

Reusable

Low Ballistic Parameter
Low L / D
Low Total Heating
External Payload

High L / D
Ablative Heatshield
Internal Payload

AFE THIN-FILM HEAT TRANSFER MODEL
IN 31-INCH M-10 TUNNEL
Streamlines

Shock shapes
- $\frac{p_2}{p_1} = 5$
- $\frac{p_2}{p_1} = 12$

Aero coepls

Forebody pressure

Forebody heating

Afterbody impingement

Wake heating

AFE EXPERIMENTAL DATA BASE
EAB/SSD/LaRC

AFE GROUND-BASED TESTING

ORIGINAL PAGE IS OF POOR QUALITY
AEROTHERMODYNAMICS BASE R&T PROGRAM

CONFIGURATION ASSESSMENT

<table>
<thead>
<tr>
<th>FY 93</th>
<th>FY 94</th>
<th>FY 95</th>
<th>FY 96</th>
<th>FY 97</th>
</tr>
</thead>
</table>

CONFIGURATION ASSESSMENT

- PLS/ACRV Preliminary Database Complete
- 2 Stage AMLS Database Complete
- Identify Preferred AMLS Concepts
- Begin Database on Selected PLS Configurations
- Complete Aerothermal Analysis (AMLS)
- Select Candidate Concepts (AMLS)

AEROTHERMODYNAMICS BASE R&T PROGRAM

PROGRAM AUGMENTATION - WHY NOW?

- NASA NOW AT CRITICAL JUNCTURE IN PLANNING THE FUTURE
- SYSTEMS DESIGNED FOR PERFORMANCE AT LOWEST LIFE CYCLE COST ARE MANDATORY
- AEROTHERMODYNAMICALLY EFFICIENT DESIGNS ARE KEY TO HIGHER PERFORMANCE MARGINS AND RESULTING LOWER COST
- CONFIGURATION ASSESSMENTS OF NEAR-TERM SYSTEMS ASSURE AGENCY IS "SMART BUYER"
- THE OAET AEROTHERMODYNAMICS CAPABILITY ADEQUATELY APPLIED TO THE BROAD RANGE OF OPTIONS WILL BENEFIT THE AGENCY/NATION

ORIGINAL PAGE 18
OF POOR QUALITY
AEROTHERMODYNAMIC TECHNOLOGY WILL GREATLY INFLUENCE THE VIABILITY AND AFFORDABILITY OF ALL FUTURE SPACE TRANSPORTATION SYSTEMS.
AEROBRAKING
(Aeroassist)
for
Transportation Thrust

External Review
of
Integrated Technology Plan
for the
Civil Space Program

June 27, 1991

Aerobraking

- Definitions
- Applications/Benefits
- Environments
- Issues
- Performance Objectives
- Technology Program
- Synthesis Report
Types of Aeroassist Maneuvers

- **Aerobraking**
  - Use of atmosphere for deceleration, generally requires L/D < 1
  - **Aerocapture**
    - Maneuver from hyperbolic trajectory or high energy orbit to lower energy orbit
  - **Orbit altitude reduction**
    - Maneuver from high altitude orbit to lower energy orbit
  - **Direct entry**
    - from orbit, either high or low altitude
    - from hyperbolic trajectory

- **Aeromaneuvering**
  - Use of aerodynamics for plane change or cross range, generally requires L/D > 1
AEROBRAKING MODES

Aerocapture
(from hyperbolic trajectory
or high orbit)

Direct Entry
(from hyperbolic trajectory
or high orbit)

Orbital Entry

AEROBRAKING APPLICATIONS

<table>
<thead>
<tr>
<th></th>
<th>All Chemical</th>
<th>Chemical/Aerobrake</th>
<th>Nuclear Thermal</th>
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</thead>
<tbody>
<tr>
<td>Lunar Return</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerocapture</td>
<td>N/A</td>
<td>Baseline</td>
<td>N/A</td>
</tr>
<tr>
<td>Direct Entry</td>
<td>Baseline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At Mars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerocapture</td>
<td></td>
<td>Baseline</td>
<td>Option</td>
</tr>
<tr>
<td>Direct Entry</td>
<td></td>
<td>Option</td>
<td>Option</td>
</tr>
<tr>
<td>Entry from orbit</td>
<td></td>
<td>Baseline</td>
<td>Baseline</td>
</tr>
<tr>
<td>Mars Return</td>
<td></td>
<td>Option</td>
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<tr>
<td>Aerocapture</td>
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<td>Option</td>
<td>Option</td>
</tr>
<tr>
<td>Direct Entry</td>
<td>Baseline</td>
<td>Baseline</td>
<td>Baseline</td>
</tr>
</tbody>
</table>

Aerobraking provides many viable mission options.
Aerobraking Applications to Mars Precursor and Robotic Missions

Mars Sample Return (2005 Time Frame)
- Chemical propulsive departure for Mars
- Aerobrake to Mars Orbit
- Separate from Earth Return Vehicle
- Aeroentry and land
- Deploy Rover and collect sample
- Ascend to orbit and rendezvous with Earth return stage
- Transfer sample
- Chemical propulsive departure for Earth
- Aerobrake to orbit or aeroentry and recovery

Mars Site Characterization Landers (2010 Time Frame)
- Chemical propulsive departure for Mars
- Aerobrake or chemical brake to Mars orbit
- Aeroentry and precision landing

Mars Robotic Missions to Remote Sites (2015-30 Time Frame)
- Either same scenario as site characterization landers
- Or deployed from approaching or orbiting Manned Missions
- Aeroentry and precision landing

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass (kg)</th>
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<tbody>
<tr>
<td>CLUSTER PAYLOAD ADAPTER</td>
<td>113</td>
</tr>
<tr>
<td>CLUSTER PAYLOAD BODY</td>
<td>838</td>
</tr>
<tr>
<td>SAMPLE RETURN CRUISE (SRO-C)</td>
<td>1641</td>
</tr>
<tr>
<td>SAMPLE IN SITELANDER (SSL)</td>
<td>1300</td>
</tr>
<tr>
<td>MAV (ABSENT VEHICLE BAY)</td>
<td>1330</td>
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<tr>
<td>TOTAL LUNAR MASS</td>
<td>5795</td>
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<tr>
<td>SAMPLE RETURNED</td>
<td>5</td>
</tr>
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</table>
Benefits of Lunar Aerobraking

- **Benefits of Lunar Aerobraking**
- **Aerobraking Application to Lunar Missions**
  - Aerobraking enables recovery/reuse of high cost elements of the Lunar vehicle (crew module, propulsion/avionics) with major reduction in initial mass in LEO (~35%) over all chemical propulsion option.
  - Entry velocities of ~11 km/sec are insensitive to return trajectory or Lunar departure point (surface, orbit, or libration point). AFE technology validation enables efficient structures with reduced design uncertainties.
Mars Short Duration Stay Venus Swing-By Missions

Benefits of Aerobraking for Mars Missions

- Mars long stay-time missions are the only type of Mars mission that are feasible with chemical all propulsive systems
  - Use of aerobraking enables a reduction in one way transit times within practical IMLEO limits. 200-270 days transit times can be reduced to 120-160 days, depending upon opportunity.

- Chemical propulsive short stay-time missions are not practical without aerobraking
  - IMLEO reduction of 30 to 60% over a chemical all propulsive system
AEROBRAKING ENVIRONMENTS

Lunar Missions:
Extension of Apollo flight experience
Entry velocity conditions the same
Significant differences in flow conditions between:
Direct entry (Apollo)
Aerobraking

Mars Missions:
Extend flight environments significantly beyond our past experience for both Mars entry and Earth return entry
Highly variable conditions with:
Opportunity year
Type of mission trajectory

EARTH ENTRY VELOCITY ENVELOPES

Shuttle
GEO Return/AFE
Lunar Return/Apollo
Return from Mars
1000 Day Mission
500-600 Day Transfer
300-400 Day Transfer
200 Day Transfer
500 Day Mission
350 Day Mission

* Inertial

Ventry*, km/sec

AE2-7
SEI AEROBRAKING/AEROCAPTURE

MARS RETURN

R - 1 M

MARS ATMOSPHERE, "AEROCAPTURE"

EARTH-MOON AEROASSIST ENVELOPE

AIR IONIZATION

AIR DISSOCIATION

PEAK HEATING - w/cm²

MARS ENTRY VELOCITY ENVELOPES

Orbital Entry

1000 Day

500 Day

Sprint 440 day

Sprint 360 Day

Transit time reduction

Ventry, km/sec
Aerobraking Challenges and Issues

There are no showstoppers

Aerobrake Deployment/Assembly

Issue: Aerobrakes are too large for conventional intact launch and require precision assembly. What is the impact of Aerobrake deployment/assembly requirements?

Answer:

- Current studies are examining:
  - Designs for simplified assembly
  - Alternatives to assembly
  - Intact launch options
  - Deployable, space rigidized

- Precision assembly is not unique to Aerobrake
  - Propellant feedline connects/disconnects are common to all configurations

- On-orbit deployment/assembly and precision assembly is required regardless of Aerobrake utilization

On-orbit assembly is a critical issue for Aerobrakes as well as all Exploration missions. Current studies are addressing a variety of options.
**Mars Vehicles Relative Sizes**

<table>
<thead>
<tr>
<th>Option</th>
<th>Chem/Aerobrake</th>
<th>Nuclear Thermal</th>
<th>Nuclear Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>50m</td>
<td>110m</td>
<td>230m</td>
</tr>
</tbody>
</table>

Chem/Aerobrake is the smallest system option. All reference concepts use Aerobrake for Mars entry/landing.

---

**CREW G-LOADS DURING AEROBRAKING**

**Issue:** Are the Aerobraking g-loads (around 5 g's) acceptable for the flight crew following extended weightlessness during transit to Mars and return

**Answer:**

- Soviet cosmonauts experienced similar (5-g) profile following 8 month in weightlessness
- Plan collaboration with Soviet M.D. cosmonaut to study effects of g-loads following weightlessness
SKYLAB AND SOVIET STUDIES INDICATE THAT FOR MISSIONS OF THREE MONTHS OR MORE, CARDIOVASCULAR READAPTATION TAKES 3-7 DAYS AND DOES NOT DEPEND ON MISSION DURATION.

First-hand reports from Soviets:

- ONE COSMONAUT FLEW A PLANE THE DAY HE RETURNED FROM AN 8 MONTH MISSION
- WALKING AFTER 8 MONTH MISSION:
  - 50 PACES THE DAY OF RETURN
  - ONE HALF MILE THE DAY AFTER LANDING
  - FIVE MILES AFTER ONE WEEK
- PLAYING TENNIS IN 4 TO 5 DAYS

Mars Aerocapture Altitude Boundaries

Issue: Do tall mountains on Mars present a hazard to Mars Aerocapture?

Answer:

- The altitude range for Aerocapture passes is between 30 and 55 KM altitude. The height of the tallest mountain is 27 KM.
- Also, mountains are highly localized and easily avoided in mission planning.

Mountains are not a Aerobraking hazard.
NAVIGATION ACCURACY FOR MARS AEROCAPTURE

Issue: Does Mars aerocapture require extreme interplanetary navigation accuracies?

Answer:

Aerocapture does require more precise navigation than propulsive maneuvers. However, current Earth based planetary navigation provides good aerocapture performance for mid L/D (0.3 - 0.5) vehicles.

Autonomous onboard optical star trackers, probably required for man rated systems, can provide greatly enhanced nav performance providing improved Aerobrake efficiency.

Navigation accuracy is an important design consideration. However, it is not a show-stopper.

CG MANAGEMENT REQUIREMENTS

Issue: The Aerobrake L/D is dependent on the proper location of the vehicle center-of-gravity. What is the required precision for location of the C.G.?

Answer: C.G. management is a design and operational issue common to all flight vehicles. Potential methods include design to minimize C.G. variations and/or to compensate for C.G. movement. These include payload location, active control/trim devices, active mass balance systems, and adaptive guidance systems. Preliminary analyses of adaptive guidance systems indicate that C.G. variations of ± 1 to 1.5% of body diameter can be accommodated. This provides a C.G. envelope of 2 to 3 feet for a 100 foot diameter Aerobrake.

The Aerobrake system can accommodate a reasonable C.G. dispersion.
ATMOSPHERIC VARIATIONS & UNCERTAINTIES

Issue: What is the Aerocapture risk caused by the Mars atmospheric uncertainties and variations?

Answer: This issue has been extensively analyzed by the Mars Atmosphere Knowledge Requirements Working Group.

Maximum Dust Storm Variations

- Limited data show large variations in pressure and density
- Dust storms greatest source of variations

Aerobrake assessment:
- State-of-the-art guidance algorithms successfully flew worst case atmospheres
- Possible TPS erosion in dust storms, but small system weight impact
- Recommended increased emphasis on Mars Observer statistical atmospheric measurements

Atmospheric variations and uncertainties can be accommodated with modest design impacts.

AEROBRAKING IN A DUSTY MARTIAN ATMOSPHERE

Vehicle configuration.

Dust particle trajectories in the shock layer.

EROSION OF GLASS SLAB

EROSION OF ABLATING AVCOAT

AE2-13
RADIATION ENVIRONMENT

Issue: Venus swingby trajectories used in 500 day class Mars missions increase the crew radiation hazards from Solar flares.

Answer: This type of trajectory is being used for both Aerobrake and NTR short duration missions. A radiation shelter is required for solar flare protection regardless of the type of trajectory. The impact of swingby trajectories on this shelter is modest.

KEY ELEMENTS OF AEROBRAKING TECHNOLOGY

An Integrated Program

- Integration of mission, design and technology issues
- Multidisciplinary technologies
  - Aero thermodynamics
  - GN&C
  - Thermal Protection
  - Structures
- Validation
  - Ground test
  - Flight test
### AEROBRAKING PERFORMANCE OBJECTIVES

<table>
<thead>
<tr>
<th>TECHNOLOGY GOAL PARAMETER</th>
<th>CURRENT SOA</th>
<th>OBJECTIVE/REQUIREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEHICLE CONFIGURATION</td>
<td>L/D ≤ 0.25-3, ground based</td>
<td>L/D 0.5 with mission margin and flexibility</td>
</tr>
<tr>
<td>AEROTHERMODYNAMICS</td>
<td>3-D models for non-equilibrium conditions, with very limited validation database</td>
<td>Validated 3-D gas codes, chemical and thermal rarefied flows, Mars gases, coupled radiative heating/massive ablation limited, validation database</td>
</tr>
<tr>
<td>GUIDANCE, NAVIGATION &amp; CONTROL</td>
<td>Entry to precise Earth surface</td>
<td>Aerobraking to precise planetary orbit; precision landing to Mars surface, autonomous navigation; adaptive, fault tolerant systems</td>
</tr>
<tr>
<td>THERMAL PROTECTION SYSTEM</td>
<td>Reusable ≤ 2800 - 3000°F; Ablative: moderate-energy (Apollo)</td>
<td>Light-weight reusable materials (lunar), increased reuse temp to ≤ 4000°F Low weight ablative materials for high energy missions at Mars and Earth return</td>
</tr>
<tr>
<td>STRUCTURES</td>
<td>Structures and TPS are ground based</td>
<td>Aerobrake mass fraction &lt; 15%, on-orbit assembly and certification</td>
</tr>
</tbody>
</table>

#### Aerobraking Technology Plan

- **Planetary**
  - Configuration Assessments
  - Aerothermo Models
  - TPS Assessments
  - Advanced Development

- **Lunar**
  - Aero Models/Wake
  - TPS Enhancement
  - Structures Demo
  - Advanced Development
  - Space based LTV

- **Mars/Earth Return**
  - Configuration Definition
  - Aerothermo Models
  - GN&C Devel
  - TPS
  - Structures
  - Advanced Development

- **Flight Experiments**
  - Flights
  - Data Assessment
  - Preliminary Planning -
    - High Energy Aerobrake Flight Experiment
  - High Energy AFE Program

---

AE2-15
Transportation Technology
Space Transportation Systems

OBJECTIVES

- **Programmatic**
  Develop Aerobraking technologies for manned lunar, robotic and manned Mars, and planetary missions.

- **Technical**
  Validated aerothermodynamic codes
  Reusable and non-reusable TPS materials
  Adaptive guidance
  Light weight structures
  Flight test validation

Aerobraking

SCHEDULE

- 1995 Mars entry probes code validation
- 1998 AFE flight data code/TPS assessment
- MRSR aerocapture validation
- 2000 Lunar LTV Codes, TPS, Assembly validated
  Comet sample return
  Codes, TPS validated
- 2002 High Energy Aerobrake Flight Experiment (HEAFE) test
- 2004 Mars mission validation
  Codes, GN&C, TPS, Structures

RESOURCES

- 1991 $0.9 M
- 1992 $0.9 M
- 1993 $4.8 M
- 1994 $9.3 M
- 1995 $14.8 M
- 1996 $20.4 M
- 1997 $23.8 M
- 1998 $22.5 M
- 1999 $18.1 M

* AA’s Discretionary Funds

PARTICIPANTS

- Langley Research Center
  Project lead, lead for technology integration, guidance, navigation, & control; and structures
  Support for aerothermodynamics and TPS
- Ames Research Center
  Lead for aerothermodynamics and thermal protection materials
- Johnson Space Center
  Lead for ground and space test
  Support for thermal protection, structures, and aerothermodynamics
- Jet Propulsion Lab
  Support for navigation

Aerobraking Sub-element

Missions, Concepts, & Operations

OBJECTIVES

- Integrate and optimize aerobrake technologies with design, operations, cost and schedule issues to meet mission requirements

Description

- Refine reference vehicle/operational concepts for technology impacts
- Define technology requirements
- Assess technology progress

SCHEDULE

- 1993 Refine lunar aerobrake reference concept/technology requirements
- 1993 Define planetary technology requirements
- 1994 Establish Mars reference concept/technology requirements
- 1995 Define High Energy Aerobrake Flight Experiment concept
- 1996 Refine Mars Aerobrake technology trades
- 1997 Assess AFE flight data impacts

RESOURCES

- 1991 $0.2 M
- 1992 $0.3 M
- 1993 $0.4 M
- 1994 $0.7 M
- 1995 $0.9 M
- 1996 $1.2 M
- 1997 $1.2 M
- 1998 $1.0 M
- 1999 $1.0 M

* AA’s Discretionary Funds

PARTICIPANTS

- Langley Research Center
  Sub-element lead
  Mission performance, vehicle concepts, operational concepts, cost estimation.

- Ames Research Center
  - Refine aerobraking human factors requirements, especially entry “g” criteria
  - Define planetary aerobraking technology requirements

AE2-16
THE L/D ISSUE

Advantages to high L/D aerobrake configurations
- More aerodynamic control authority — greater corridor width, greater capability for load-relief, heat rate-relief
- Convective heating dominates — better able to quantify at the systems level
- Greater cross-range, if required

Drawbacks to high L/D aerobrake configurations
- Higher ballistic coefficient — greater structural and TPS mass
- Packaging difficulties — c.g. control
- Integrated vehicle design — aerobrake and payload design cannot be separated

Trade-off Approach
- Identify the minimum required aerobrake L/D to insure a successful aerocapture maneuver

MINIMUM AEROBRAKE L/D, JR MARS AEROCAPTURE
1° CORRIDOR WIDTH REQUIREMENT, 5-G DECELERATION LIMIT
OBJECTIVES
Extend, validate and apply computational codes for the prediction of aerodynamic and aerothermodynamic characteristics of Earth and planetary aerobraking maneuvers.

Description: Combine the use of:
- Computational Fluid Dynamics (CFD)
- Computational Chemistry
- Experimental test
- Flight experiments

SCHEDULE
- 1993 Lunar concept forebody/wake models developed
- 1994 Planetary models defined
- 1995 Lunar concept model validation
- 1996 Establish High Energy Aerobraking Flight Experiment aerothermodynamic objectives
- 1997 Assess AFE flight data
- 1998 Mars concept model validation

RESOURCES
- 1991 $0.2 M
- 1992 $0.3 M
- 1993 $1.4 M
- 1994 $2.5 M
- 1995 $2.7 M
- 1996 $3.0 M
- 1997 $3.0 M
- 1998 $2.4 M
- 1999 $2.0 M

* AA's Discretionary Funds

PARTICIPANTS
- Ames Research Center
  Sub-element lead. Development of validated phenomenological models. Validated CFD codes and ground based high enthalpy experiments.
- Langley Research Center
  Validated engineering codes, configuration analysis and parametric experimental studies.
- JSC
  Configuration assessment

VALIDATION OF SEI AEROTHERMODYNAMICS CODES
TWO-TEMPATURE MODEL VS EXPERIMENTS

MARS ENTRY
N₂-CO₂ Mixture in Shock Tube, V=8.9 km/s

LUNAR RETURN
Air in Shock Tube, V=11.3 km/s
STATE-OF-THE ART CFD FOR REAL GAS FLOWS

Temperature Contours

OBJECTIVES
- Develop and validate advanced guidance techniques, including appropriate sensors, which autonomously compensate for mission variations in navigation, aerodynamics, and atmospheric properties.

Description:
- Enhanced Interplanetary navigation
- Validatable adaptive guidance algorithms
- Atmospheric density sensors
- Test bed/flight demonstration

SCHEDULE
- 1993 Identify guidance/sensor architectures
- 1993 Define Mars reference navigation system
- 1994 Concept demo of G&N system
- 1995 Define High Energy Aerobrake Flight Experiment G&N objectives
- 1996 Validate lunar G&N
- 1997 Define G&N for flight test
- 1998 Mars test bed demo

PARTICIPANTS
- Langley Research Center
  Sub-element lead
  Adaptive guidance algorithms, atmospheric sensors, test bed
- Jet Propulsion Laboratory
  Interplanetary navigation support
- Johnson Space Center
  Validation

RESOURCES
- 1991 $0.1 M
- 1992 $0.2 M
- 1993 $0.3 M
- 1994 $1.1 M
- 1995 $1.7 M
- 1996 $2.2 M
- 1997 $2.7 M
- 1998 $2.5 M
- 1999 $1.8 M

* AA's Discretionary Funds
ADAPTIVE GUIDANCE METHODS

- Responsible for guiding the vehicle through the atmosphere in the presence of off-nominal conditions to a set of specified atmospheric exit parameters

- Mission success is measured in terms of the post-aerocapture ΔV requirements

LaRC Algorithm Features
- Predictor-corrector formulation
- 3 DOF inner-loop simulation
- Orbital energy control
- Load-relief
- Orbital plane control
- Deceleration feedback
- Bank-angle modulation is the only control

POST-AEROCAPTURE ΔV REQUIREMENTS
MULTIPLE OFF-NOMINAL EFFECTS

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<tr>
<td>1</td>
<td>Load-relief (nominal trajectory)</td>
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<tr>
<td>2</td>
<td>Load-relief, random density profile</td>
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<tr>
<td>3</td>
<td>Load-relief, random density profile, horizontal density wave</td>
</tr>
<tr>
<td>4</td>
<td>Load-relief, aerodynamic misprediction</td>
</tr>
<tr>
<td>5</td>
<td>Load-relief, random density profile, horizontal density wave, aerodynamic misprediction</td>
</tr>
</tbody>
</table>

Trajectory number

AE2-20
Aerobraking Sub-element

Objective:
- Develop, model, and validate thermal protection materials which meet the reusability requirements of manned lunar missions and the high combined (convective and radiative) heat rate capability for Mars aerocapture and Earth return.
- Description:
  - Extend Shuttle type tile and carbon-carbon reusable materials
  - Tailor ablators to Mars capture and Earth return
  - Develop new materials

Schedule:
- 1993: Assess TPS requirements for manned & robotic missions
- 1994: Evaluate materials for MRSC mission
- 1995: Deline TPS requirements for High Energy Aerobrake Flight Experiment
- 1996: Model and test high energy aerobrake materials
- 1997: Evaluate AFE TPS test results
- 1998: Design TPS for HEAFE

Resources:
- 1991: $0.1 M
- 1992: $0.15 M
- 1993: $0.8 M
- 1994: $1.5 M
- 1995: $3.0 M
- 1996: $4.0 M
- 1997: $5.0 M
- 1998: $5.0 M
- 1999: $4.2 M

*AA's Discretionary Funds

Participants:
- Ames Research Center
  Sub-element lead
  RSI enhancement
  Ablator tailoring/development
  Ceramic composites > 4000 °F
- Langley Research Center
  Carbon-carbon materials/strutures
- JSC
  Carbon-carbon materials
  Material validation

Reusable Thermal Protection Systems (TPS)

Maximum service temperature (°F)

- 6000
- 5000
- 4000
- 3000
- 2000
- 1000

Light weight TPS for ASTV/Mars manned mi
Re cusible TPS for LEO Transfer Vehicle

- Development of higher temperature TPS materials is a NASA critical techn
THERMAL PROTECTION SYSTEMS TEMPERATURE CAPABILITY

POST-TEST PHO" 'GRAPHS OF RCC AND
ZrB₁ + 20 v/o SIC SAMPLES

Test conditions: Test time = 8 min, Cold wall heat flux = 240 BTU/hr·sec
Slag. pressure = 0.046 atm, Slag. enth. = 18,000 BTU/lbm

LTV - t1n2a
RCC
Recession: 78 mls
Weight change: 1.31 gm
Peak temp.: 3700°F

SIC coating lost after approximately 100 sec

Cerac - t2n4a
ZrB₁ + 20 v/o SIC
Recession: -1 mls
Weight change: 0.01 gm
Peak temp.: 3300°F

Adherent, thin, glossy coating formed on sample

NASA
Ames Research Center Thermal Protection Materials Branch

ORIGINAL PAGE IS OF POOR QUALITY
OBJECTIVES
- Demonstrate integrated structural concepts which meet the combined requirements of mission performance and operations. Performance requires low weight while supporting dynamic inertial and thermal loadings and meeting operational requirements for launch packaging, assembly/deployment, and inspection/certification.

- Description:
  - Assembly test bed
  - Lunar Aerobrake test bed
  - Mars Aerobrake test bed

SCHEDULE
- 1993 Define Lunar structural/assembly concepts
- 1994 Define reference Lunar structure
- 1995 Assembly test bed demo
- 1997 Define reference Mars structure
- 1998 Lunar structural test bed
- 2002 Mars structural test bed

PARTICIPANTS
- Langley Research Center
  Sub-element lead. Integrated structural concepts for thermal structural loadings, assembly, and inspection/certification.
- JSC
  Integrated design requirements, structural assessment and validation.

RESOURCES
- 1991 $ 0 M
- 1992 $ 0 M
- 1993 $ 0.7 M
- 1994 $ 1.1 M
- 1995 $ 2.3 M
- 1996 $ 3.7 M
- 1997 $ 4.8 M
- 1998 $ 5.2 M
- 1999 $ 4.0 M

STAGNATION POINT HEATING PULSES DURING MARS AEROBRAKING

$V_0 = 8.8 \text{ km/sec}, \text{ AFE SHAPE}, (I/D)_{max} = 0.3$

$\rho/C_p = 100 \text{ kg/m}^2$

$\tau_a = 16 \text{ sec}$

\[
\begin{align*}
\text{Undershoot} & : Q = 3.3 \text{ kJ/cm}^2 \\
\text{Overshoot} & : Q = 3.5 \text{ kJ/cm}^2
\end{align*}
\]

- Equil. red.
- Total

MASS FRACTION = 13 %
Fully configured aerobrakes are too large to launch inside a rocket payload shroud

Flexible structure solutions
- Foldable
  - Martin Marietta

Rigid structure solutions
- Assembled in space
  - Boeing Huntsville
  - McDonnell Douglas
- Deployable
  - No major effort
- Integral launch
  - Boeing Huntsville
Figure 6a. Mock-Up Design

Figure 6b. Integrated Mockup

Figure 7. Mockup Layout and Proposed Assembly Operations in the UWTP
OBJECTIVES

- Define and establish the integrated ground and flight test programs necessary for the validation of aerobraking technologies.
- Description
  - Define integrated testing requirements
  - Define requirements for flight test demonstrations beyond AFE
  - Define and compare ground facility options including development of new facilities

SCHEDULE

- 1993 Define Aerobraking validation data requirements
- 1994 Assess flight experiment vs ground test options
- 1995 Define flight experiment concepts
- 1996 Define flight experiment instruments
- 1998 Recommend flight experiment concept

RESOURCES

- 1991 $ 0 M
- 1992 $ 0 M
- 1993 $0.1 M
- 1994 $0.3 M
- 1995 $0.8 M
- 1996 $1.6 M
- 1997 $1.5 M
- 1998 $1.0 M
- 1999 $0.9 M

PARTICIPANTS

- JSC
  - Sub-element lead
  - Flight experiment concepts
- Langley Research Center
  - Ground test facilities
  - Flight experiments
- Ames Research Center
  - Ground testing
  - Flight experiments

AEROASSIST FLIGHT EXPERIMENT (AFE)

Mission Profile - Simulates STV Aerobrake

- Deploy from Shuttle
- Accelerate to Atmospheric Entry
- Simulate Gasdynamic Trajectories
- Return Aerobrake
- Return to Earth Orbit for Shuttle Pick-up
### TRANSPORT TECHNOLOGY

**Technology Flight Experiments**

#### OBJECTIVES

<table>
<thead>
<tr>
<th>Programmatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Validate and demonstrate Aerobraking technologies for manned Mars missions.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical</th>
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<tbody>
<tr>
<td>Validated aerothermodynamic codes demonstrate high temperature TPS materials. Adaptive guidance demonstration.</td>
</tr>
</tbody>
</table>

### SCHEDULE

- 1993 Begin concept planning
- 1997 AFE flight test
- 1997 Start experiment development
- 2002 HEAFE flight test
- 2004 Mars mission validation

#### RESOURCES

<table>
<thead>
<tr>
<th>Year</th>
<th>Amount</th>
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<td>1997</td>
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<td>1998</td>
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<td>$110M</td>
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<td>2000</td>
<td>Continue</td>
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</tbody>
</table>

#### PARTICIPANTS

- Langley Research Center: Aerothermodynamics, GN&C, Structures
- Ames Research Center: Aerothermodynamics, TPS
- Johnson Space Center: Structures, TPS
- Jet Propulsion Lab: Navigation
- Marshall Space Flight Center: Spacecraft

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### Synthesis Report on Aerobrake

- **Contents:**
  - Aerobrake purged from main discussion and art
  - Aerobrake not listed among key technologies
  - Aerobrake listed as a backup option
  - AFE supported

OAET Aerobrake technology Team Preparing Response To Synthesis report
• Aerobraking provides many beneficial mission options

• Several design, operational, and technology issues
  But
  There are no show stoppers
  The issues are understood
  There is a strong foundation of existing technology
  and experience

• There are significant benefits of technology advancements

• A strong, focused, multidisciplinary technology program is needed to
  validate and enhance Aerobraking technologies
AEROASSIST FLIGHT EXPERIMENT

PRESENTATION

TO

SPACE SYSTEMS

and

TECHNOLOGY ADVISORY COMMITTEE

JUNE 27, 1991

AEROASSIST FLIGHT EXPERIMENT

ORIGINAL PAGE IS OF POOR QUALITY
AEROASSIST FLIGHT EXPERIMENT

PROGRAM GOAL

- PROVIDE CRUCIAL TECHNOLOGY FOR DESIGN AND DEVELOPMENT OF EFFICIENT AEROASSISTED SPACE TRANSFER VEHICLES (ASTV)

PROGRAM OBJECTIVES

- CHARACTERIZE THE AEROTHERMODYNAMIC ENVIRONMENT IN THE GEO AND / OR LUNAR RETURN REGIMES
- VALIDATE COMPUTATIONAL FLOW FIELD CODES WITH MEASUREMENTS NOT AVAILABLE FROM PREVIOUS FLIGHT VEHICLES OR GROUND FACILITIES
- DEVELOP GUIDANCE AND CONTROL TECHNIQUES FOR A LOW L/D VEHICLE IN A VARIABLE DENSITY ATMOSPHERE
- EVALUATE PERFORMANCE OF CANDIDATE THERMAL PROTECTION SYSTEMS

NASA
National Aeronautics and Space Administration

AEROASSIST FLIGHT EXPERIMENT (AFE)
Mission Profile: Simulates OTV Aeropass

Deploy from Shuttle
Accomplished: Atmospheric Entry
Simulate Geosynchronous Return Aeropass
Return to Earth Orbit for Shuttle Pick-up
AEROASSIST FLIGHT EXPERIMENT (AFE)

DEPLOYMENT CONFIGURATION

AEROBRAKE

CARRIER VEHICLE

RMS GRAPPLE FIXTURE

ASTRO LATCH TRUNNIONS

STAR 63D SRM

ASTV FLIGHT REGIME

VELOCITY, kft/sec

ALTITUDE, kft

VELOCITY, kft/sec

ALITUDE, kft

18 20 24 28 32 36

200

150 16 20 24 28 32 36

250

300

350

• PEAK HEATING

SIGNIFICANT NON-EQUILIBRIUM

IONSATION

LUNAR RETURN

APOLLO ENTRY

EQUILIBRIUM

1% IONIZATION

AFE

SHUTTLE ENTRY

APOLLO ENTRY
AEROGAIST FLIGHT EXPERIMENT

ASTV FLIGHT ENVIRONMENT

- RAREFIED FLOW
- THICKENED SHOCK
- IONIZED SHOCK LAYER
- NONEQUILIBRIUM CHEMISTRY
- RADIATIVE HEATING
- CATALYSIS (CONVECTIVE HEATING)
- PAYLOAD
- AEROBRAKE
- BASE CONVECTIVE AND RADIATIVE HEATING

AEROGAIST FLIGHT EXPERIMENT

- ASTV DESIGN ISSUES
  - SHOCK LAYER RADIATION
  - SURFACE CATALYSIS
  - THERMAL PROTECTION SYSTEM MATERIALS
  - WAKE FLOWS/HEATING
  - AERODYNAMICS/CONTROL

- AFE EXPERIMENTS
  - RADIATIVE HEATING EXPERIMENT (RHE)
  - MICROWAVE REFLECTOMETER IONIZATION SENSOR EXPERIMENT (MRIS)
  - WALL CATALYSIS EXPERIMENT (WCE)
  - HEAT SHIELD PERFORMANCE EXPERIMENT (HSP)
  - ALTERNATE THERMAL PROTECTION MATERIALS EXPERIMENT (ATPM)
  - FOREBODY AEROTHERMAL CHARACTERIZATION EXPERIMENT (FACE)
  - BASE FLOW AND HEATING EXPERIMENT (BFHE)
  - AFTERBODY RADIOMETRY EXPERIMENT (ARE)
  - AERODYNAMIC PERFORMANCE EXPERIMENT (APEX)
  - RAREFIED-FLOW AERODYNAMICS MEASUREMENT EXPERIMENT (RAME)
  - PRESSURE DISTRIBUTION/AIR DATA SYSTEM EXPERIMENT (PD/ADS)
AEROASSIST FLIGHT EXPERIMENT

STATUS

- PROGRAM
  - PROJECT REPLANNED TO ACCOMODATE 1991 AND 1992 FUNDING CONSTRAINTS
  - EMPHASIZE CARRIER VEHICLE DESIGN COMPLETION AND EXPERIMENT DEVELOPMENT
  - LAUNCH PLANNED FOR JULY 1996

- CARRIER VEHICLE
  - COMPLETED REVIEW OF NASA DESIGN - OCTOBER 1990
  - DESIGN TRANSFERRED TO CONTRACTOR - FEBRUARY 1991
  - STRUCTURAL TEST ARTICLE IN FINAL DESIGN - INITIATE FABRICATION SEPTEMBER 1991
  - MAJOR AVIONIC SUBSYSTEMS ORDERED/READY FOR PROCUREMENT
  - CONTRACTOR CDR SCHEDULED FOR JUNE 1992

- AEROBRAKE
  - CDR COMPLETED OCTOBER 1990
  - STRUCTURAL TEST ARTICLE DESIGN/FABRICATION COMPLETE - IN TEST
  - FLIGHT STRUCTURE/TPS DESIGN/FABRICATION 95% COMPLETE
AEROASSIST FLIGHT EXPERIMENT

STATUS

- NINE EXPERIMENT CRITICAL DESIGN REVIEWS COMPLETE
- 3 OF 4 MICROWAVE TRANSMIT/RECEIVE MODULES DELIVERED FOR ENGINEERING UNIT
- THERMAL CAPACITANCE TESTS OF TRIAXIAL ACCELEROMETER PLATE COMPLETE AND ELECTRONIC FILTER DESIGN VERIFIED THROUGH BREADBOARD TESTS
- ACCEPTANCE TESTING OF FLIGHT PRESSURE TRANSDUCERS 70% COMPLETE
- INSTRUMENTED TILES MANUFACTURED FOR AEROBRAKE STRUCTURAL TESTS
- TYPE "K" TC WIRE AND ALL EXTENSION WIRE ACCEPTANCE/CALIBRATION TESTS COMPLETE
- BREADBOARD TESTING OF BASE FLOW VISUALIZATION SYSTEM IN PROGRESS
- INTEGRATED BREADBOARD TESTING OF RADIOMETER SYSTEM IN PROGRESS
- TWO RADIOMETER WINDOW DESIGNS HAVE SURVIVED ARC JET TESTING AT EQUIVALENT EQUILIBRIUM TEMPERATURE OF 2900°F
### AFE Status

**Aeroassist Flight Experiment**

**NOA, OBS & Cost Actuals**

Baseline 4/91

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<table>
<thead>
<tr>
<th>ACTIVITIES</th>
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<th>CY93</th>
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**AFE Status:** 6/7/91

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**NOA, OBS & Cost Actuals**

Baseline 4/91

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Graph showing NOA, OBS, and Cost Actuals from Oct 1, 87 to Oct 1, 96.
• PROGRAM SUMMARY
  - NINE EXPERIMENT CRITICAL DESIGN REVIEWS COMPLETE
    • ENGINEERING DEVELOPMENT HARDWARE IN FABRICATION
  - AEROBRAKE STRUCTURAL DESIGN COMPLETE
    • STRUCTURAL TEST ARTICLE FABRICATED AND IN TEST
  - CARRIER VEHICLE
    • DESIGN RESPONSIBILITY TURNED OVER TO MCDONNELL DOUGLAS
    • PRIMARY STRUCTURE DESIGN COMPLETE
    • CONTRACTOR CDR ON SCHEDULE FOR JUNE 1992

SUMMARY

• AEROBRAKING IS A CRUCIAL TECHNOLOGY OPTION FOR FUTURE SCIENCE AND EXPLORATION MISSIONS
  - FLIGHT EXPERIMENT DATA IS CRITICAL TO EFFICIENT / REUSABLE SPACECRAFT FOR LUNAR / GEO MISSIONS USING AEROBRAKING
  - FLIGHT DATA PROVIDES THE FOUNDATION AND CONFIDENCE TO PURSUE AEROBRAKING FOR MARS ENTRY AND RETURN TO EARTH AS BACKUP / ALTERNATIVE TO NUCLEAR SYSTEMS
  - AEROBRAKING TECHNOLOGY DEVELOPMENT IS NEEDED FOR SCIENCE, SAMPLE RETURN, AND PROBE MISSIONS

• AFE IS REQUIRED TO VALIDATE AND DEMONSTRATE THIS TECHNOLOGY

• SIGNIFICANT PROGRAM PROGRESS HAS BEEN ACHIEVED
ENTRY TECHNOLOGY FOR PROBES AND PENETRATORS

For

SSTAC REVIEW OF INTEGRATED TECHNOLOGY PLAN

System Studies
Aerothermodynamics
Thermal Protection Materials
Aeroshell Structures
GN&C

By

James O. Arnold
NASA Ames Research Center
6/25/91

OUTLINE

• NEEDS FROM SCIENCE COMMUNITY (F. SURBER, JPL)
• APPROACH TO FILL SELECTED NEEDS
• EXAMPLES
• FUNDING
• SUMMARY - ISSUE
TECHNOLOGY NEEDS

SOLAR SYSTEM EXPLORATION MISSIONS
✓ · MARS NETWORK (PENETRATORS, HARD LANDERS)
✓ · NEPTUNE ORBITER (PROBE)
✓ · PLUTO FLYBY (PROBE OPTION)
✓ · URANUS ORBITER (PROBE)
✓ · JUPITER GRAND TOUR (PROBE, PENETRATORS, HARD LANDERS)
✓ · ASTEROID AND COMET MISSIONS (PENETRATORS, IMPACTORS, HARD LANDERS)
✓ · VENUS PROBE
✓ · MERCURY ORBITER (PENETRATORS, HARD LANDERS)

SPACE EXPLORATION INITIATIVE MISSIONS
· LUNAR AND MARS SITE RECONNAISSANCE (IMPACTORS)
· SITE CERTIFICATION AND ENGINEERING DATA COLLECTION (PENETRATORS, HARD LANDERS)
· LUNAR AND MARS ENVIRONMENTAL STATIONS (HARD LANDERS)
· NAVIGATION BEACONS (HARD LANDERS)
· PHOBOS/DEIMOS SCIENCE (PENETRATORS, HARD LANDERS)
✓ · VENUS SCIENCE (PROBES FOR VENUS FLYBY TRAJECTORIES)
✓ · RTG SURVIVABILITY - GALILEO - CASSINI

SPACE SCIENCE TECHNOLOGY: IN-SITU SCIENCE
PROBES AND PENETRATORS

STATE OF THE ART ASSESSMENT
✓ Entry Technology Required

• CURRENT PROBE & PENETRATOR TECHNOLOGIES ARE FUNCTIONALLY ACCEPTABLE, BUT LARGE, HEAVY AND EXPENSIVE.
• DoD HAS DEVELOPED A WEALTH OF APPLICABLE TECHNOLOGIES, BUT MANY KEY ELEMENTS FOR SPACE MISSIONS ARE MISSING.
• DETAILED ASSESSMENT:
✓ · ATMOSPHERIC PROBES HAVE A LONG HISTORY: SOUNING ROCKETS, PIONEER VENUS, VIKING, GALILEO, CASSINI
· SANDIA HAS TESTED THOUSANDS OF INSTRUMENTED PENETRATORS
· HIGH-G ELECTRONICS AND SENSORS FOR SMART GUN-LAUNCHED MUNITIONS EXCEED PENETRATOR REQUIREMENTS
· SDIO IS DEVELOPING MINI-SUBSYSTEMS & COMPONENTS FOR BRILLIANT PEBBLES
· CRAF PENETRATOR DESIGN WAS WELL DEVELOPED WHEN DELETED FROM THE PROJECT, BUT THE TECHNOLOGY HAD NOT YET BEEN DEMONSTRATED AT THE SYSTEM LEVEL
· HARD LANDERS WERE BUILT AND SUCCESSFULLY DROP TESTED IN THE 70'S BUT NONE HAVE FLOWN SPACE MISSIONS
✓ · APPLICATION OF NEW TECHNOLOGIES AND INSTRUMENTS COULD REDUCE THE SIZE, MASS AND COST DRAMATICALLY WHILE IMPROVING THE SCIENCE RETURN

AE4-2
PROBES AND PENETRATORS

TECHNOLOGY CHALLENGES

TECHNOLOGY DEVELOPMENT CHALLENGES:

- REDUCE SIZE AND COST DRAMATICALLY AND INCREASE SCIENCE RETURN CAPABILITY
- SURVIVE EXTREME ENVIRONMENTS OF PRESSURE, TEMPERATURE AND SHOCK

SPECIFIC CHALLENGES INCLUDE:

- MINIATURIZED PROBE & PENETRATOR SENSORS
- IMPLANTING & ANCHORING DEVICES
- IMPACT ATTENUATORS AND ABSORBERS
- HIGH-G (1000-10,000 G's) SUBSYSTEMS, INSTRUMENTS & COMPONENTS FOR PENETRATORS
- MODERATE-G (40 G's) SUBSYSTEMS, INSTRUMENTS & COMPONENTS FOR HARD LANDERS
- ADVANCED THERMAL CONTROL SYSTEMS FOR PENETRATORS
- HIGH PERFORMANCE, STORABLE BIPROP ENGINES
- MINI, HIGH-THRUST, HIGH-PRECISION THRUSTERS
- HIGH ENERGY AEROCAPTURE, AEROMANEUVERING & DEPLOYABLE AEROSHELLS
- DESCENT/IMPACT ATTITUDE CONTROL

SPACE SCIENCE TECHNOLOGY: IN-SITU SCIENCE

PROBES AND PENETRATORS

OTHER DEVELOPMENT EFFORTS

- OAET PROGRAMS
  - R&T BASE
    - AERODYNAMICS
    - SPACE ENERGY CONVERSION
    - PROPULSION
    - MATERIALS & STRUCTURES
  - SPACE EXPLORATION
    - SPACE NUCLEAR POWER
    - HIGH CAPACITY POWER
    - SURFACE POWER & THERMAL MANAGEMENT
  - SPACE SCIENCE
    - SAAP
    - (OPTOELECTRONICS SENSORS - POTENTIAL PROGRAM)
    - (MICRO INSTRUMENTS AND IN-SITU SENSORS - POTENTIAL PROGRAM)
  - TRANSPORTATION
    - ADVANCED CRYOGENIC ENGINES
    - AEROASSIST (AEROMANEUVERING)
    - AUTONOMOUS LANDING
    - AEROASSIST FLIGHT EXPERIMENT
    - (HIGH ENERGY AEROBRACING FLIGHT EXPERIMENT - POTENTIAL PROGRAM) HEAFE
  - SPACE PLATFORMS
    - DEEP SPACE PLATFORMS

- DoD PROGRAMS
  - SDIO BRILLIANT PEBBLES
  - SMART GUN-LAUNCHED MUNITIONS
  - SANDIA PENETRATOR PROGRAM
PROBES AND PENETRATORS

TECHNOLOGY ELEMENT PROGRAM OBJECTIVES

- COMPLETE INITIAL SYSTEM CONCEPT, DESIGN AND REQUIREMENT STUDIES 1994
- DEMONSTRATE LABORATORY MODELS OF MINIATURIZED SENSORS 1997
- DEMONSTRATE LABORATORY MODEL OF DESCENT/IMPACT ATTITUDE CONTROL 1997
- DEMONSTRATE PROTOTYPE IMPLANTING AND ANCHORING DEVICES 1998
- DEMONSTRATE PROTOTYPE IMPACT ATTENUATORS AND ABSORBERS 1998
- DEMONSTRATE PROTOTYPE MODERATE AND HIGH-G STRUCTURES & PACKAGING 1998
- DEMONSTRATE ADVANCED PENETRATOR THERMAL CONTROL SUBSYSTEMS 1998
- DEMONSTRATE PROTOTYPE HIGH-G POWER, DATA & COMMUNICATIONS SUBSYSTEMS 1998
- DEMONSTRATE PRECISION MINI-THRUSTERS 1998
- DEMONSTRATE A PROTOTYPE LIGHTWEIGHT PROBE AEROSHELL 1999
- CONDUCT HARD LANDER FLIGHT EXPERIMENT WITH INTEGRATED SYSTEMS 2000
- CONDUCT PENETRATOR FLIGHT EXPERIMENT WITH INTEGRATED SYSTEMS 2000
- DEMONSTRATE PROTOTYPE MODERATE AND HIGH-G MINI RTGS IN THE 100 WATT CLASS 2003

***FLIGHT EXPERIMENT COSTS NOT INCLUDED IN TECHNOLOGY ELEMENT RESOURCE ESTIMATES.

PROBES & PENETRATORS - BUDGET

PROBE TECHNOLOGY $M

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AE4-4
APPROACH

SELECT THREE MISSIONS FOR STUDY & CONDUCT SUFFICIENT TO TRANSFER TECHNOLOGY TO INDUSTRY

- MARS PRECURSOR MISSIONS
  MESUR
  MRSR

- OUTER PLANET ENTRY
  NEPTUNE PROBE

- HIGH SPEED EARTH RETURN
  COMET SAMPLE RETURN
  RTG PROBLEM

MESUR Windward Surface Flow Properties

Temperature

\[ \frac{\rho}{Kg/m^2} \]
\[ 800.88 \]
\[ 600.00 \]
\[ 400.50 \]
\[ 300.05 \]
\[ 200.03 \]
\[ 150.87 \]
\[ 130.83 \]
\[ 120.29 \]
\[ 110.94 \]
\[ 100.30 \]
\[ 90.76 \]
\[ 80.12 \]
\[ 70.48 \]
\[ 60.84 \]
\[ 51.20 \]
\[ 41.56 \]
\[ 31.92 \]
\[ 12.28 \]
\[ 01.64 \]

95.6% CO\(_2\)
2.7% N\(_2\)
1.9% H\(_2\)
0 = 2 m

Density

Pressure

AE4-5

ORIGINAL PAGE IS OF POOR QUALITY
NEPTUNE PROBE "COLD WALL" HEATING RATES

\[ V_e = 25 \text{ km/sec} \]
\[ \gamma_e = -50^\circ \]

STAG. PT. HEATING RATE (kW/cm²)

PEAK TURBUL. CONV. ≈ 12 kW/sec

TIME, sec

COMET SAMPLE RETURN VEHICLE "COLD WALL" HEATING RATES

\[ V_e = 15.5 \text{ km/sec} \]
\[ \gamma_e = -8^\circ \]
\[ D = 1.85 \text{ m} \]

STAG. PT. HEATING RATE (kW/cm²)

TIME, sec

TOTAL

EQUIL. RADIATION

AE4-8
ISSUE

FUNDING TIME LINE/AMOUNT DO NOT CORRELATE WITH
SCIENCE REQUIREMENT
SSTAC/ARTS

A&R Systems
AUTOMATION & ROBOTICS
INTRODUCTION

PRESENTED TO:
SPACE SYSTEMS AND TECHNOLOGY ADVISORY COMMITTEE

JUNE 26, 1991
MCLEAN, VA

PRESENTED BY:
DR. MELVIN D. MONTEMERLO
MANAGER OF AUTOMATION AND ROBOTICS
CODE RC
NASA HDQ
WASHINGTON, D.C.

A & R AGENDA

Wednesday
9:45 A&R Overview
10:45 Discussion
11:00 Artificial Intelligence
11:45 AI Discussion
12:00 Lunch
1:00 Telerobotics
1:45 TR Discussion
2:00 Rovers
3:00 Break
3:15 Rover Discussion
3:30 A&R Discussion & Conclusions
5:00 Adjourn

Montemerlo
Friedland

Friedland
Weisbin

Weisbin
Lavery, Bedard

Bedard
Daly
ITP A&R Committee Task

SUPPORT THE AUGUSTINE COMMITTEE RECOMMENDATION TO PROVIDE AN EXTERNAL REVIEW OF NASA'S PLAN TO AUGMENT THE SPACE TECHNOLOGY PROGRAM.

BY

DRAFTING A&R RECOMMENDATIONS FOR INCLUSION INTO JOE SHEA'S SSTAC REPORT.

PREVIOUS A&R RECOMMENDATIONS

- National Commission on Space "Pioneering the Space Frontier"
- Sally Ride report: Leadership & America's Future in Space:
- Augustine Committee
- 1987 ASEB "Space Technology to Meet Future Space Needs"
- AIA "Key Technologies for the 1990s"
- The Automation and Robotics Panel (ARP) - 1985
- The Advanced Technology Advisory Committee - 1985
- SSTAC meeting at ARC - 1990
A&R PROGRAM OBJECTIVES

- PROVIDE A&R TECH TO ENABLE BOLD CIVIL SPACE PROGRAM
- SERVE AS NATIONAL FOCUS FOR SPACE A&R TECHNOLOGY
- DEVELOP & VALIDATE THE BASIC TECHNOLOGY TO ACHIEVE SUCCESSIVELY HIGHER LEVELS OF AUTONOMOUS SPACE OPERATIONS AND TELEROBOTICS
- HASTEN THE USE OF A&R WITHIN NASA
- DEVELOP WORLD-CLASS A&R R&D CAPABILITY WITHIN NASA
- PROMOTE SPACE A&R R&D IN INDUSTRY AND ACADEMIA
- INCREASE THE SUPPLY OF NEW PH.D.s IN SPACE A&R

MACHINE INTELLIGENCE (A&R)

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## A&R NEEDS/OPTOPUNITIES

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A&R BENEFITS

- INCREASED PROBABILITY OF MISSION SUCCESS
- REDUCTION OF THE "MARCHING ARMY"
- INCREASED SAFETY MARGINS
- INCREASED RETURN FROM SCIENCE DATA
- INCREASED OPERATIONAL CAPABILITY IN SPACE
- AMELIORATE EFFECT OF BIMODAL AGE DISTRIBUTION
  (Capture knowledge of retiring employees)
- ABILITY TO DEAL WITH MASSIVE DATABASES ON COMPLEX
  LONG-LIVED SYSTEMS
- INTEGRATION OF DATA FROM NUMEROUS SOURCES FOR
  IMPROVED DECISION AIDING
- INTELLIGENT AUTONOMY OF SPACE SYSTEMS
  - Frees astronauts from housekeeping
  - Unmanned spacecraft can recognize & cope with unexpected
  - Enable planetary exploration

A&R PROGRAM ELEMENTS

EXPLORATION
- ROVERS

R&T BASE
- ARTIFICIAL INTELLIGENCE R&T BASE
- TELEROBOTICS R&T BASE

OPERATIONS
- ARTIFICIAL INTELLIGENCE (mission ops asst, data analysis,
  autonomous control, and large KBs)
- TELEROBOTICS (robotics, telerobotics, teleoperation,
  telepresence, and terrestrial robots)
- TECHNICAL FLIGHT EXPERIMENTS (Under Code RX)
  - FTS DTF
A&R TECHNOLOGIES

TELEROBOTICS
- Control
- Human Interface
- Sensing & Perception
- Intelligence
- Mechanisms
- Architecture
- Processors
- Systems integration
- Implementation Infrastructure

ARTIFICIAL INTELLIGENCE
- Planning & Scheduling
- Learning
- Large Knowledge Bases
- Knowledge Rep.
- Model-based Reasoning
- Human Interface
- Diagnosis
- Real-time Control
- Validation & Verification
- Systems Integration

ROVERS
- Mobility
- Navigation
- Vision
- Power
- Autonomy
- Processors
- Payload(SAAP)
- Sys. Integration

SYNERGISM

A&R AT NASA (9-88 MOD 6-91)


- TRADITIONAL AUTOMATION ONLY
- OAST TAKES FIRST STEPS IN A&R
- CONGRESSIONAL A&R MANDATE
- A&R TO BE CENTERPIECE OF STATION
- EXTREME POSITIONS PRO AND CON
- EXTREME VIEWS ON CAPABILITIES OF AI AND TR
- REVOLUTION, NOT EVOLUTION
- OK TO HAVE R&T BASE
- A&R HONEYMOON

- MUCH NASA A&R PLANNING AND WORK
- CENTER & HDQ ROLES STILL EVOLVING
- AI IS REALISTIC; TR IMMATURE
- NOT OK TO HAVE R&T BASE (CSTI)
- ROVER ADDED; SEI TO 4X A&R $

- AI "WINS" CHANGE CLIMATE
- NASA DROPS FTS,OMV,SSS
- TR PROGRAM "FOCUSSED"
- TR GROUND APPLICATIONS
- JAPAN TR REVIEW
- TR "SYSTEMS" FOCUS
- EVOLUTION, NOT REV
- HONEYMOON OVER
- AUGUSTINE TO 4X A&R $
- OK TO ADD AN R&T BASE
## A&R Funding ($M)

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** ROVER funding in FY92 includes $0.8M in R&T base and $0.75M in Telerobotics

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**ARTIFICIAL INTELLIGENCE**
AI OPPORTUNITIES AT NASA

Space and Aeronautical Mission Control
- reduce manpower needs
- reduce training time
- improve critical decision making

Management and Analysis of Science and Engineering Data
- increase science return from under-analyzed data
- improve effective use of bandwidth capacity
- conduct in-situ analysis on planetary surfaces

Onboard Monitoring, Diagnosis and Control
- enhance safety by discovery of incipient failures
- free crew to conduct mission tasks
- provide realtime capabilities beyond human levels

Preservation and Utilization of Life-cycle knowledge
- capture knowledge throughout design, construction, test and operations
- integrate knowledge from many disparate sources
- provide for multiple use of generic knowledge

NASA Infrastructure
- procurement, office automation, etc.

AI BENEFITS

- Speed-up of work
- Cost saving on internal operations.
- New product & services.
- Changes in way of doing business.
- Improve quality of consistency of decision making.
- Return on investment.
- Capturing people's know how & disseminating it.
- Crisis management.
- Stimulating innovation.
- Reduced training time.
AI: Accomplishments

- AI in use at all NASA centers
- Turned Mission Control from negative to positive at JSC, JPL
  - RDTS and SHARP were major "wins"
- AUTOCLASS Bayesian learning tool used on IRAS data
  - also widely distributed
- JSC applications won national award for innovative AI applications
- Implemented numerous AI systems at JSC and JPL
- Developed world class AI capability
  - widely published
  - highly visible at all national and international AI symposia
  - major in-house strengths in planning, scheduling, learning, and
design & reasoning about physical systems

Al: The Delta

STATE OF THE PRACTICE:

- Embedded stand-alone rule-based monitoring diagnostic
  expert systems used in Mission Control (RTDS, SHARP)
- Bayesian learning (AUTOCLASS) used on time-independent data
- Hubble Space Telescope batch scheduling

FUTURE STATE OF THE PRACTICE:

- Coordinated distributed diagnostic systems capable of model-based
  as well as experiential reasoning in Mission Control
- Embedded real-time systems for scheduling, control and diagnostics
- Space system autonomous health monitoring and management
- Intelligent scientific instruments which monitor and modify their
  protocols for increased science payoff
- Life-cycle knowledge capture and maintenance for space systems
- Reactive real-time scheduling for Shuttle processing,
- Use of massively parallel processors to amplify AI capabilities
- Widespread use of AI in NASA infrastructure (e.g. procurement)
- AI programs which learn (modify themselves based on experience)
- AI tools for scientific and engineering data analysis
- Intelligent tutoring systems
- Natural language interfaces for large databases
- Data visualization tools used for scientific & engineering analyses
AI PROGRAM: Tasks

Intelligent Assistance for Mission Operation
- Automated Scheduling Tools
- Advanced Interaction Media
- SHARP
- RTDS
- Guidelines: Human Interface with AI
- EXODUS Shell
- KATE - LOX
- Ops. Mission Planner
- AI for Software engineering
- Shuttle Ground Processing Scheduling

Center
ARC
ARC
JPL
JSC
JSC
JSC
JPL
JPL
JSC
ARC

Scientific and Engineering Data Analysis Techniques:
- P.I. in a Box
- Automatic Classification and Theory Formation
- Scientific Analysis Assistant
- NASA Infrastructure Expert Systems
  - PC-based scheduler
  - ADPE planning expert system
  - Intelligent Purchase Request system

ARC
ARC
JPL
JSC
JPL
ARC

Autonomous Control:
- DTA-GC Instrument Control System
- Intelligent Interacting agents
- Integration of Symbolic and Numeric Control
- Machine Learning for Sys. Maint. & Improvement
- Predictive Monitoring
- Space Station Power Expert System
- F.A.D (Power) Cooperative Expert System
- Diagnosis of Physical Systems

ARC
ARC
ARC
ARC
JPL
LeRC
MSFC
ARC

Knowledge Base Technology:
- Large-Scale Knowledge Base
- Knowledge Acquisition & Use During Design
- Distributed Knowledge Base Management

ARC
ARC
GSFC
AI Program ($M)

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PROPOSED

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IMPLICATIONS

Baseline - Keeps up with inflation*
Constrained - Modest growth in outyears*
Strategic - Program doubles in 5 years.

* - assuming low inflation rate

---

AI PROGRAM:
Implications of funding profiles

BASELINE
- New areas added only as current tasks are rolled over.
- Rate of impact on NASA about same as now.

CONSTRAINED
- New areas added at the rate of one every two years
- Areas of Learning, multiple interactive systems, and control will be having effect in late 1990s.
- Modest increase in funding to academia.

STRATEGIC
- Healthy program growth with applications at all centers and fundamental work increased at ARC, JPL, academia and industry.
- New areas to be added include: integrated cognitive architectures, distributed problem solving, AI with massively parallel computing, and intelligent interacting agents.
AI: CONCLUSIONS

- AI PROGRAM HAS HAD A FIRST ORDER EFFECT ON NASA
- AI PROGRAM IS WORKING CLOSELY WITH POTENTIAL USERS
- ARC AND JPL AI GROUPS ARE WORLD CLASS
- EXISTING FUNDAMENTAL WORK SHOULD BE TRANSFERRED TO R&T BASE
- PROGRAM HAS ERODED IN ACTUAL-YEAR DOLLARS SINCE FY88
- "CONSTRAINED" BUDGET IS MINIMUM RECOMMENDED FOR PROGRAM WITH PROVEN IMPACT.
- WITH AI BEING AN A.I.A. KEY TECHNOLOGY, THE INVESTMENT WILL PAY TOP DIVIDENDS
- CURRENT MIX OF APPLICATION AND FUNDAMENTAL WORK SHOULD CONTINUE
NASA TELEROBOTICS OPPORTUNITIES/NEEDS

IN-SPACE
- EVA servicing & assembly
- Cranes
- IVA processing

TERRESTRIAL
- Manufacturing
- STS processing
- Satellite inspection

PLANETARY
- assembly and servicing
- IVA processing
- science operations
SPACE TELEROBOT SPECTRUM

TYPES OF TELEROBOTS

<table>
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<tr>
<th>SERVICERS</th>
<th>ON-OBJECT</th>
<th>TERRESTRIAL</th>
<th>MOON/MARS</th>
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<tr>
<td>- FTS</td>
<td>- VACUUM PLASMA SPRAY ROBOT FOR SME</td>
<td>- EXOSKELETON FOR SITE MAINTENANCE</td>
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<tr>
<td>- SPDM</td>
<td>- ORBITER / 747 MATE/DEMATE DEVICE</td>
<td>- LUNAR VEHICLE UNLOADER (LEVPU)</td>
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CRANES

- STS RMS
- SSF RMS
- VEHICLE ASSY

MOBILE ROBOTS

- OMV
- ETS-7

SPECIAL PURPOSE DEVICES

- NODE & STRUT ASS'Y
- STS PCR FILTER INSPECTION

IN-SPACE

- ENABLE IN-SPACE ASSEMBLY OF LARGE PLATFORMS & VEHICLES
- ENABLE SERVICING WHERE EVA NOT POSSIBLE
- ASSIST EVA ASTRONAUT (EG RMS AS A PLATFORM)
- INCREASED SAFETY
- FISHER PRICE REPORT - LARGE SPACE SYSTEMS WILL REQUIRE MUCH EVA SERVICING
- REDUCED CREW SIZE
- REDUCE ASTRONAUT HOUSEKEEPING TIME (EG CAGE CLEANING)
- TEND A PLATFORM DURING UNMANNED PHASES.

TERRESTRIAL

- SAFETY (EMERGENCY RESPONSE VEHICLES)
- COST REDUCTION AND IMPROVED CAPABILITY IN SATELLITE TESTING (THERMAL-VACUUM TESTS)
- COST REDUCTION AND IMPROVED PERFORMANCE IN MANUFACTURING AND REFURBISHING STS COMPONENTS
- INCREASED SAFETY AND REDUCE TURNAROUND TIME IN ORBITER GROUND PROCESSING
TR: The Delta

STATE OF THE PRACTICE

- STS RMS, Canada's teleoperated crane, is the only current remote manipulator in space. (1981-present)
- SSF FTS, a US-designed servicer has had components fabricated, which may be flight tested on DTF-1
- Viking Martian lander had a robotic scoop & soil analyzer. (1975)
- Lunar Surveyor had a robotic claw and soil analyzer (1966-68)
- Soviet Lunakhod was remotely controlled from Earth (1970)

FUTURE STATE OF THE PRACTICE

- Terrestrial robots widely used in space system fabrication and test
- Terrestrial robotic vehicles used in emergency handling
- Terrestrial robots used in processing of Shuttle
- Space telerobots using supervisory control from the ground
- Space teleoperators that can be controlled by a single operator
- Fleet of space telerobots in use for various applications (cranes, EVA servicers, assemblers, free-flyers, IVA robots)
- Satellites with resident robot
- Planetary robots for servicing, assembly, science, manufacturing

FUTURE TELEROBOTS IN SPACE

OPERATIONAL FLIGHT SYSTEMS

- Canadian Special Purpose Dexterous Manipulator
- Canadian SSF Remote Manipulator System
- Japanese JEM Small Fine Arm
- Japanese JEM Remote Manipulator System
- French HERMES Remote Manipulator System

EXPERIMENTS

- Japanese ETS-7 Free-flyer
- German ROTEX in Spacelab
- American FTS DTF-1
NASA SPACE ROBOTICS
(X indicates program cancelled or delayed)

CODE M
- Space Shuttle Remote Manipulator System Operations- (Code MEO)
  X - Orbital Maneuvering Vehicle ------------------------------- (Code ML)
X - Satellite Servicer System flight demonstrations----------- (Code MD)
X - Space Station Flight Telerobotic Servicer (FTS)---------- (Code MT)
X - FTS Evolution studies ------------------------------------- (Code MT)
? - Advanced Development ------------------------------------- (Code MT)
- Space Station cooperation with foreign partners ------- (Code MF)

CODE R
- Automation and Robotics program -------------------------- (Code RC)
  - Telerobotics
  - Artificial Intelligence
X - Planetary Rover
X - Vehicle Servicing and Processing
X - Exploration Automation and Robotics
- Centers of Excellence in Space Engineering----------------- (Code RS)
  - grant to Rensselaer Polytechnic Institute
- Materials and Structures program ------------------------- (Code RM)
X - Rover sample acquisition, analysis and preservation
X - In-space assembly & construction (of large space vehicles)
? - SEI robotics and rover studies

SPACE TELEROBOTICS:
THE CHALLENGES

1) INFO BASE FOR FUTURE SPACE ROBOTIC
   - SERVICERS, CRANES, ROVERS
   - WHEN TO USE TELEOPERATION, TR & ROBOTICS

2) SUPERVISORY CONTROL FROM THE GROUND

3) HIGH FIDELITY SIMULATION FOR FULL-TASK DEMOS

4) ROBOTIC IMPLICATION FOR SYSTEM DESIGN

5) DESIGN FOR ROBUST CAPABILITY (FAULT TOLERANCE)
   - ABILITY TO WORK IN DEGRADED MODE
   - DESIGN FOR MAN-RATING

6) TERRESTRIAL ROBOTICS FOR SPACE SYSTEMS

7) DEVELOP INFRASTRUCTURE OF ROBOTICISTS AND FACILITIES
   - UNIVERSITY GRANTS
   - CENTER TEAMS AND EQUIPMENT

8) IMPROVED COMPONENTS & ARCHITECTURES FOR SPACE TR

AR1-16
### Telerobotics Program

#### Teleoperations:
- Cranes: JSC, Challenge 8,7,1
- Advanced Teleoperation: JPL, Challenge 8,1,2
- Free-flying manipulators: U. MD., Challenge 7,3,1
- Exoskeletons: JPL, Challenge 1,8,4

#### Telerobotics (Supervisory Control):
- Telerobotic Inspection: JPL, Challenge 8,1,2
- Compound Manipulators: LaRC, Challenge 8,4

#### Robotics:
- Structural Assembly: LaRC, Challenge 4,1
- Multiple Autonomous Robots (Stanford): ARC, Challenge 7,8
- Fault Tolerant Actuators (Univ of Texas): JSC, Challenge 7,5,8
- Servicer Automation: GSFC, Challenge 1,4

#### Ground robotics:
- Ground Emergency Response Vehicle: JPL, Challenge 6
- STS Tile Inspection and Maintenance: KSC, Challenge 6
- PCR Filter Inspection Robot: KSC, Challenge 6
- Vacuum plasma spray robot for SSME: MSFC, Challenge 6

---

### Telerobotics: Program Accomplishments

#### Programmatic
- Infrastructure (Expertise and Facilities): 7,3
- Coord among Centers & with Outside: 7,1
- Over 40 Graduates now in TR & Related Fields: 7,1

#### Technical
- "Peg in Hole" Tasks with Compliance: 8,2
- Single Arm Puts Single Strut in Node: 8,2
- Control of Multiple Arms with Single Joystick: 8,4
- Human Control in Simulated Microgravity: 3,1,7
- Generalized Force-Reflecting Hand Controllers: 8,2
- "Smart End Effector": 8,2
- Precursor to FTS Hardware (LTM): 1,5,8,7
- Vision-Based Stopping of a Spinning Satellite: 2,8
- Teleoperated Assembly of EASE in Water Tank: 7,1
- Teleoperated Assembly of Access Structure: 1
- End-Point Control of Flexible Arms: 7,8,4
- "Geometric Reasoning for Robot Task Planning": 8,2

---

* NASA OAET*
**TELEROBOTICS: "LEVEL 0" MILESTONES**

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<tr>
<td>1992</td>
<td>COOP MANIPULATION FOR FREE-FLYING TELEROBOTS</td>
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<tr>
<td>1992</td>
<td>TELEOPERATED DEMO OF SOLAR MAX REPAIR</td>
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<td>1992</td>
<td>HEPA FILTER INSPECTION ROBOT FOR PCR AT KSC</td>
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<td>1993</td>
<td>AUTOMATED ASSEMBLY OF NON-PERMANENT STRUCTURE</td>
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<td>1993</td>
<td>MULTI-SENSOR ROBOT INSPECTION FOR GAS LEAKS, ETC</td>
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<td>1994</td>
<td>ROBOTIC PLASMA SPRAY GUN FOR SSME</td>
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<td>COMBUSTION CHAMBER FABRICATION</td>
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<td>1994</td>
<td>SHUTTLE TILE INSPECTION &amp; WATERPROOFING ROBOT</td>
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<td>1994</td>
<td>DUAL-ACTUATOR WITH REDUNDANT MOTORS, ENCODERS, GEAR TRAINS</td>
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<td>1995</td>
<td>EXOSKELETON TELEPRESENCE SYSTEM</td>
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<td>1996</td>
<td>PERFORM ROBOT ASSY OF SOLAR-DYNAMIC STRUCTURE</td>
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**TR PROGRAM NEEDS**

- FOCUS ON ROBUST TR SYSTEMS PERFORMANCE IN HI-FI SIM
- "RAPID PROTOTYPING" APPROACH TO SYSTEM CAPABILITY DEFINITION AND ENHANCEMENT
- HIGHER LEVELS OF FIDELITY AND SYSTEM INTEGRATION IN TR EXPERIMENTS (WHICH INCREASE COST)
- SOME APPLICATIONS WIN
  - TERRESTRIAL APPLICATIONS ARE FASTER
  - AS IN AI, CHERRY-PICK THE EASY ONES FIRST
  - TO TRAIN IN-HOUSE PEOPLE ON TR SYSTEMS
- TO BE GEARED TO:
  - CREATING THE CONFIDENCE FOR PROJECT MANAGERS TO WRITE TR REQUIREMENTS
  - A RANGE OF POSSIBLE TR APPLICATIONS, BECAUSE IT IS IMPOSSIBLE TO PREDICT WHICH WILL HAPPEN FIRST
  - GROWING A CADRE OF EXPERTS, WHO ARE READY
- SUFFICIENT FUNDING TO TAKE ADVANTAGE OF EXPERTISE IN ACADEMIA AND INDUSTRY
INTEGRATION OF A ROBOT INTO A SYSTEM

INTEGRATION OF COMPONENTS INTO A ROBOT

COMPONENT DEVELOPMENT
- CONTROL
- SENSORS
- MECHANISMS
- INTELLIGENCE
- HUMAN INTERFACE
- ELECTRONICS
- PROCESSORS
- POWER
- ARCHITECTURE

COMPONENT
- SELECTION
- MODIFICATION
- INTEGRATION

OPTIMIZE SYSTEM PERFORMANCE, NOT ROBOT PERFORMANCE.

SPECIFIC TR PROGRAM NEEDS

- A FEW NEAR TERM TASKS WHICH CAUSE NASA TO USE ROBOTS

- INCREASE THE SET OF SPACE TR FOCI
  - CURRENTLY (INSPECTION, ADV TELEOPERATION FOR SERVICING, FREE-FLYERS, CRANES, EXOSKELETONS)
  - ADD: IVA ROBOTICS, COMPOUND MANIPULATORS, ROBOTIC ON-SATELLITE SERVICING)

- RE-INSTITUTE THE R&T BASE

- FIND PEOPLE EXPERIENCED IN REAL-WORLD ROBOT IMPLEMENTATION AND MAKE THEM PART OF OUR TEAM

- JOINT RESEARCH TASK WITH JAPANESE

- CODIFY CURRENT TR STATE OF THE ART

- ESTIMATE SPACE TR INFRASTRUCTURE

- A TASK ON LOW-COST TR WITH LOW COMPUTATIONAL POWER

- DEVELOPMENT OF A TR EVALUATION TOOL

NASA GAET

AR1-19
Impressions of Japanese Approach to Robotics Technology Development

- Pick limited set target task(s) quickly
- Focus on getting target tasks done robustly (Don't try to get one robot to do too much)
- Minimalist approach (use only technology needed)
- Design Robot as part of system (The Systems Approach)
- Stepwise, not continuous, evolution toward autonomy (Stay with a paradigm until its successor is ready) (Teleoperation, Supervisory Control, Autonomous robots)
- "Rapid Prototyping" approach (build series of prototypes; don't design first for evolution) (minimize development time)
- invest for long term payback to research

TELEROBOTICS CONCERNS

- NASA CANCELLED ALL U.S. PLANNED SPACE ROBOTS
- LACK OF NASA TR REQTS UNDERMINES R&D PROGRAM
- IN 20 YRS, NASA HAS STARTED & ENDED FOUR TR R&T PROGRAMS
- 1-SHOT FTS PROGRAM COULD DRAIN LONG-TERM R&T PROGRAM
- PERCEPTION THAT SPACE TELEROBOT WILL COST OVER $1B
- FAILURE OF MANY TELEROBOTICS DEMONSTRATIONS
- LACK OF ROBOTICISTS WITH EXPERIENCE IN DESIGNING AND IMPLEMENTING REAL ROBOTS IN THE REAL WORLD
- COST & SIZE OF SPACE TR INFRASTRUCTURE NOT APPRECIATED
- NEED REASONABLE-COST ACCESS TO SPACE FOR EXPERIMENTS
- TIME LAG FROM RESEARCH TO USE CAUSING OVER-PROMISING.
- U.S. LOSING TO FOREIGN POWERS IN SPACE TELEROBOTICS
- REPEATED REPLANNING OF PROGRAM FUNDING QUADRUPLING
TR Program ($M)

HISTORY

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Baseline 16.2 16.6 17.4 18.2 18.9
Constrained 16.2 18.9 20.4 21.6 24.9
Strategic 16.2 19.6 25.9 33.2 42.1

IMPLICATIONS

Baseline - Keeps up with inflation*
Constrained - Modest growth in outyears *
Strategic - Program doubles in 4 years.

* - assuming low inflation rate

TR PROGRAM: Implications of funding profiles

BASELINE
- New areas added only as current tasks are rolled over.

CONSTRAINED
- New areas added at the rate of one every two years
- Areas of IVA robotics, coop task with Japanese, database codification, low-computation robotics, and telerobotics evaluation tool to be added in that order.
- Modest increase in funding to academia.

STRATEGIC
- Healthy program growth with applications at all centers and fundamental work increased at JPL, LARC, academia and Industry.
- New areas to be added include are same as those listed in constrained program except they would be added more quickly.
TELEROBOTICS: Conclusions

NEAR TERM OBJECTIVES:
- STAY ALIVE
- CREATE A MARKET

- It is imperative that the Code RC TR program continue in existence since it is the only Space TR technology program in the US.
- The constrained budget is the needed to have a near term impact on NASA ground and space robotics.
- The goal of the TR program should be to do whatever necessary to give project managers the confidence to write TR requirements.
- NASA needs more access to more expertise in robotic systems implementation.
- An R&T Base should be reinstituted to insure the development of adequate component technologies in space robotics.

A&R CONCLUSIONS AND RECOMMENDATIONS
TWO IMPORTANT OPEN ISSUES

- Space Station
- Space Exploration Initiative

PREVIOUS A&R RECOMMENDATIONS

- National Commission on Space "Pioneering the Space Frontier"
- Sally Ride report: Leadership & America's Future in Space:
- Augustine Committee
- 1987 ASEB "Space Technology to Meet Future Space Needs"
- AIA "Key Technologies for the 1990s"
- The Automation and Robotics Panel (ARP) - 1985
- The Advanced Technology Advisory Committee - 1985
- SSTAC meeting at ARC - 1990
**A&R PROPOSED FUNDING PROFILES ($M)**

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**A&R - three proposals**

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<td>Focussed TR</td>
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<td>- large aug in 96-97</td>
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<td>portion of AI &amp; TR moved to R&amp;T Base in FY93</td>
<td>AI &amp; TR AUGMENTED</td>
<td>SAME AS CONSTRAINED, BUT LARGER AUG.</td>
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CONCLUSIONS

ARTIFICIAL INTELLIGENCE
- EXEMPLARY R&D PROGRAM
- CONVERTED GROUND CONTROL FROM ANTI TO PRO
- MULTIPLE APPLICATIONS NOW IN USE
- OUTSTANDING GROUP OF RESEARCHERS
- EXCELLENT RAPPORT WITH USER COMMUNITY
- GREAT INTERCENTER COMMUNICATIONS
- SUPERB RELATIONSHIP WITH ACADEMIA & INDUSTRY

TELEROBOTICS
- THRU INFANCY AND ADOLESCENCE, NOW LEAN & FOCUSSED
- WILL HAVE EFFECT ON NASA ROBOTICS USE IN < 2 YRS
- DIFFICULT ENVIRONMENT TO AFFECT SPACE TR SOON
- NOW FOCUSSED ON NEAR-TERM TERRESTRIAL APPLICATIONS
  AND SET OF LIKELY SPACE ROBOTICS PARADIGMS
- EXCELLENT DRAW ON UNIVERSITY EXPERTISE
- FUNDAMENTAL WORK IS SMALL, DUE TO IMMEDIATE NEED
  TO SEEK NEAR TERM TO STAY ALIVE
- NEEDS EXPERTISE IN ROBOT SYSTEM IMPLEMENTATION

ROVER
- R&D NEEDED NOW FOR PROJECTS 10-15 YRS OUT
- NEEDS TO EXPAND AND EVALUATE ALTERNATIVES

RECOMMENDATIONS

AI
- EXAMPLE FOR OTHER CODE R PROGRAMS
- KEY TECH WILL BE CENTRAL TO NASA'S FUTURE
- CONTINUE TO FOSTER WITH DOUBLING OF $ IN FIVE YEARS
- TAKE MORE ADVANTAGE OF ACADEMIA AND INDUSTRY

TR
- TR WILL BE SURELY PART OF NASA'S FUTURE
- MORE IMPT TO KEEP R&D ALIVE, GIVEN PROJECTS TERMINATED
- INSURE SOME NEAR TERM TERRESTRIAL "WINS"
- WIDEN SET OF SPACE TR PARADIGMS BEING WORKED
- RE-INSTITUTE THE R&T BASE
- DOUBLE TR FUNDING IN FIVE YEARS;
  AND, ADD $20M FOR FLIGHT EXPERIMENT

ROVER
- PARAMOUNT FOR ANY EXPLORATION SCENARIO, SO INSURE
  FUNDING CONTINUATION.
- COVER SPECTRUM OF ROVER TYPES AND ARCHITECTURES
- CANNOT COVER R&T ON ALL SUBSYSTEMS;
  FOCUS ON EVALUATION OF SYSTEM CONCEPTS
PREVIOUS A&R RECOMMENDATIONS

1984 - Public Law 98-371
1985 - The Automation and Robotics Panel (ARP)
1985 - The Advanced Technology Advisory Committee (ATAC)
1986 - Paine's National Commission on Space
      "Pioneering the Space Frontier"
1987 - Sally Ride report: Leadership & America's Future in Space:
1987 - ASEB "Space Technology to Meet Future Space Needs"
1987 - AIA "Key Technologies for the 1990s"
1990 - SSTAC meeting at ARC
1991 - Stafford's Space exploration "Synthesis Study"
1991 - Augustine's "Report of the Advisory Committee on Future of the Space Program"

PUBLIC LAW 98-371
(July 18, 1984)

"Provided further, that the Administrator shall establish an Advanced Technology Advisory Committee in conjunction with NASA's Space Station program and the Committee shall prepare a report by April 15, 1985,

identifying specific space station systems which advanced automation robotics technologies, not in use in existing spacecraft, and

that the development of such systems shall be estimated to be no less than 10 per centum of the total space station costs."
Automation and Robotics Panel:
25 Feb 1985

Recommendations:
1. Achieve high level of Space Station automation
2. Hook and Scar IOC station for evolving A&R
3. Grade Phase B contractors for A&R inclusion
4. Search actively for and allow for A&R breakthroughs
5. Include specific A&R features in IOC
6. Demonstrate specific A&R capabilities prior to IOC
7. Shift from Earth-based to space-based operations control
8. Specifies A&R technologies for NASA to lead, leverage & exploit
9. Fund A&R R&D at $100 - $190M/yr (85% research & 15% demos)
10. Sustain aggressive A&R R&D program even if Station is delayed
11. Goals for A&R R&D broader than Station
12. High level management responsibility for A&R R&D
13. External review panel
14. Coordinate with other organizations doing A&R R&D
15. Transfer A&R technology to other NASA applications
16. Use A&R for NASA operations both in space and terrestrial
17. Establish incentive schemes for participation in A&R

FIRST REPORT (4-1-85) of Advanced Technology Advisory Committee (ATAC)

Congress has seen fit the wisdom of developing a new generation of automation and robotics technology. Such a general-purpose technology would be efficient and flexible enough to meet needs as yet unspecified. Therefore, Congress has given NASA a mandate to advance the state of the art in automation and robotics not only for the benefit of space station, but for the benefit of the US economy as a whole.
"The U.S. must substantially increase its investment in its space technology base. We recommend: a threefold increase in NASA's base technology budget to increase this item from two to six percent of NASA's total budget. This growth will permit the necessary acceleration of work in many critical technical fields from space propulsion and robotic construction to high performance materials, artificial intelligence and the processing of non-terrestrial materials. We also recommend: Special emphasis on intelligent autonomous systems. Cargo trips beyond lunar distance will be made by unpiloted vehicles; the earliest roving vehicles on the Martian surface will be unpiloted; and processing plants for propellants from the materials on asteroids, Phobos, or Mars will run unattended. To support these complex, automated, remote operations, a new generation of robust, fault-tolerant pattern-recognition automata is needed. They must employ new computers, sensors and diagnostic and maintenance equipment that can avoid accidents and repair failures. These systems must be capable of making the same common sense corrective actions that a human operator would make. These developments by NASA should also have broad application to 21st century U.S. industry."

"Robotic and human exploration and surveying of substantial areas of the Moon and Mars. This effort will begin on the Moon with autonomously operated vehicles teleoperated from Earth, and on Mars with vehicles featuring substantial artificial intelligence. Robots will be followed by the first astronaut crews operating from Lunar and Martian outposts and bases."
Leadership & America's Future in Space: the Sally Ride Report

Concerning Mars sample return:
"As it is defined, this initiative places a premium on advanced technology and enhanced launch capabilities to maximize the scientific return. It requires aerobraking technology for aerocapture and aeromaneuvering at Mars, and a high level of sophistication in automation, robotics, and sampling techniques."

Concerning the Outpost on the Moon Initiative:
"Beginning with robotic exploration in the 1990s, this initiative would land astronauts on the lunar surface in the year 2000.... The initial phase would focus on robotic exploration of the Moon. Depending on the discoveries of the Observer, robotic landers and rovers may be sent to the surface to obtain more information."

Concerning the Mars Exploration Initiative:
"This initiative would carry our comprehensive robotic exploration of Mars in the 1990s. These missions would perform geochemical characterization of the planet, and complete global mapping and support landing selection and certification."

Space Technology to Meet Future Needs: an ASEB report

"Up until now most operations in space have been performed manually, but the proper role for man in space is supervisory. Robots can relieve the requirements for extravehicular activity, with its attendant hazards, and perform functions that man cannot perform or reach places that man cannot go. Robots for space differ from their terrestrial brethren. They must operate in zero gravity and they must be multipurpose and adaptable. Needless to say, advances in robotics will benefit both manned and unmanned missions."

CONCLUSIONS ON A&R
"Automated systems can augment human capabilities by performing mundane, repetitious or dangerous tasks, and can both increase human productivity and conduct tasks infeasible for humans; automation will be increasingly important in unmanned missions as well. While much can be gleaned from terrestrial experience, microgravity, long transmission delays and the space environment dictate special design and protection considerations. Light, limber manipulators will interact with dynamically active elements such as structures, transportation elements, and free-flying satellites. Advancing sensing and control techniques will be needed to sense the environment and interact with the tasks. Artificial intelligence will be needed for advanced information processing, along with trainable systems for unknown environments."
Space Technology to Meet Future Needs: an ASEB report

Chapter 8
Automation, Robotics and Autonomous Systems
Pages 78 to 85

8 Automation, Robotics, and Autonomous Systems

BACKGROUND
The time has come to add a new technology, automation and robotics, to the other major technologies—propulsion and power, materials, and information management—that are considered essential to U.S. capability to operate effectively in space. There are three reasons: affordability, achievability, and need.

There is an analogy between the evolution of space systems and military aircraft that may be helpful to cite. For a long period, the technologies considered critical to advancing the capability of military aircraft were propulsion, materials and structures, and aerodynamics. A time came when aircraft information and guidance and control systems became central to success that their underlying technology took its place beside the other, traditional technologies. Today the capability has advanced to such concepts as the pilot's apprentice and total in-cockpit simulation. The pilot manages but the automation system flies the mission. A similar step change in the level of operations is in store for the space enterprise; but the magnitude of the step will be much larger.

Except for specific instances (e.g., deep-space missions and Shuttle flight path control), NASA's use of automation and robotics in space has been limited. The primary reason that spaceworthy robotic capability does not exist is due to lack of investment in the underlying technologies. The United States has managed to "get by" to date because

- For manned missions: (a) missions have been short and intense, allowing the use of large ground crews for mission control; and (b) astronauts have historically been "pilots" rather than space operators.
- For unmanned missions: (a) spacecraft have been considered "disposable" and were not designed to be serviced on orbit; and (b) Earth orbiting spacecraft are readily commanded from the ground because of easy communication (relative to deep-space missions).

Changes driving the need for automation and robotics in space include vast increases in mission duration objectives and complexity (e.g., most of the "easy" space science has been done); a major change in the primary role of astronauts to in-space workers (which will be intensified in the Space Station era); and the deployment of in-space serviceable assets.

STATUS
Future missions of NASA will rely increasingly on automation, robotics, and autonomous systems for the following reasons:

1. Safety of humans in space: Exposure of humans to hazardous environments such as EVA, nuclear and hazardous chemical fuel handling, and high-radiation zones should be minimized.

2. Increased human productivity: Routine and/or hazardous tasks can be automated, and crew time-consuming EVA preparation can be minimized by use of robots.

3. Performance of tasks that are infeasible for humans: Robots can greatly enhance human capabilities for such tasks as moving large structures, capturing spinning satellites, and controlling complex systems.

4. Enabling new missions to other planets: Mobility and manipulation aids for manned missions and automated systems for complex unmanned missions, e.g., Mars rover/sample return, will provide new capabilities.

The cost of maintaining humans in space is extremely high, even in LEO; therefore, each human must be supported by systems that
can enhance astronaut effectiveness to the utmost. Each human must be free of mundane and repetitive tasks—of mind or hand—so that the unique judgment and dexterity that only humans possess are optimised. All other tasks should be carried out by machines.

Human EVA is extremely expensive, involving extensive preparation time and monitoring by other humans, in addition to costly equipment and procedures. In the future, this can usually be a task for free-flying robots, and in microgravity they can have some remarkable capabilities. They can be light, nimble, and dexterous. They can travel and maneuver. They can be any size, including quite large. And they can operate effectively in teams.

Such machines could be part of U.S. space systems beginning about the year 2000, but only if the technological base for them is developed in a timely and sustained way. It is true that some of the technology required for space automation will be developed independently of the space program—especially components of greater and greater capacity (with less and less volume and power required). But other critical aspects are space peculiar, and will not be available unless they are pursued vigorously by NASA itself. Two examples are the human/machine interface and free-flying robots in microgravity. Such robots will be so fundamentally different from those that will evolve in the Earth-bound environment that they will never be available if NASA does not develop their underlying technologies (e.g., control of flexible lightweight manipulators, and maneuvering and manipulating at microgravity). The cost and waste of human EVA time will constrain space operations to a small fraction of what could be.

Ongoing programs include research and development for Earth-application automation and robotics, e.g., within the DARPA, SDIO, the National Science Foundation, and industrial robotics and teleoperation programs. The current support of space automation and robotics R&D is almost entirely NASA funded (at a level of about $5 million a year starting in FY 1985).

An exception to this is the technology of mobility and autonomous navigation that could be applied to a planetary rover. This technology is currently supported primarily by the DARPA Autonomous Landing Vehicle (ALV) program and some Army programs.

In 1983 the Automation and Robotics (A&R) Panel, with non-NASA specialists in automation across the spectrum of the space-relevant technologies, was commissioned. The panel addressed the question of which automation and robotics technologies were critical for NASA to support (and which would not require NASA support) in order for space operations—and specifically, operations of the Space Station—to advance to the new high level that only automation can make possible. Attention was given to timing and evolution, and to selected space demonstrations, as well as to the sequence of primary technology-base achievements that would be necessary for fully-automated, minimum-cost, high-capability operation of the Space Station by the year 2010. Drawing upon experience with similar DARPA programs, the A&R Panel recommended that the cost of the necessary national technology development program should be between $100 million and $150 million in 1990.

KEY TECHNOLOGY AREAS AND OPPORTUNITIES

Some of the technology required for space automation and autonomous systems will be developed independently of the space program, and NASA should certainly take advantage of those developments. But other critical aspects, such as human-machine interface and free-flying robots in microgravity, are space peculiar, and will not be available unless they are pursued vigorously by NASA itself.

The microgravity and space exposure environment dictates special design and protection considerations for automated and robotic space systems, as opposed to terrestrial systems. Long transmission delays and limited or absent crew in space imply higher levels of supervisory control and local automation. The requirements for flexible operation in the performance of unspecified tasks in an uncertain environment stand in contrast to the repetitive tasks of industrial robots, for example, and place special demands on validation.

Thus, although considerable research, development, and use of automation and robotics technologies are in place for terrestrial applications, space applications pose unique requirements which the NASA program must consider. These include the following:

1. Design will be driven by low-mass requirements that limit power, size, and communication bandwidth (in the case of robotics,
mass limitations require mechanisation of light, limber manipulators interacting with dynamically active elements such as structures, transportation elements, and free-flying satellites.

2. Multipurpose robots will be required for operations in the complex, uncertain, hazardous space environment (relative to factory robots that tend to be limited, well-defined, repetitive functions) because launching a wide variety of special-purpose robots is too costly and may result in single-point failures, and many space tasks are not pre-determinable, thus flexibility and adaptability are essential.

3. Very high reliability and safety requirements (especially in manned systems) place special requirements on the validation of intelligent systems.

4. Advanced sensing and manipulation/control techniques will be needed for the space environment.

5. This, in turn, will require advanced information processing of a variety of data types; the processing will require the use of AI to achieve a high degree of autonomous capability.

6. AI techniques must be specially selected for the requirements and constraints of space missions.

7. Most important, the man-machine interface in especially critical in manned space missions where each crew member will perform a variety of functions requiring interaction with automated and robotic systems.

There is lively speculation about how humans can most effectively interact with machines in space—with the "thinking" experimental systems that will assist in mission management and scientific discovery as well as with "doing" robots. Command at the most sophisticated level is the goal. Extensive research will be needed to develop a system for interaction between humans in space and the autonomous systems that serve them, and so one but the space community will develop it.

Key technology areas that need to be addressed include:

- rapid, precise control of flexible, lightweight manipulator systems;
- cooperation between manipulators and between robots;
- mobility and maneuverability;
- telepresence human interaction and effective displays;
- trainable, model-based systems to be used in unknown environments;
- real-time expert systems and predictors;
- tools and effectors;
- sensing and perception;
- advanced in-space computing systems; and
- maintainability.

**RECOMMENDATIONS**

An aggressive space automation and robotics program will benefit both manned and unmanned missions by allowing increased human productivity both in space and on the ground, increasing science or commercial return on investment, reducing operations costs, improving safety and comfort of space operations, and enabling numerous space achievements and operations otherwise not realizable.

Incentive funding in this area should be directed toward both basic advances in the key enabling technologies and applied research focused on the special needs of automated and robotic systems. "Demonstrations" activities should focus on (1) technology integration into automated and robotic systems (because there are considerable technological issues in such systems integration), and (2) validation of the utility, reliability, safety, and so on of automation and robotics technologies in space applications.

The university community, with its basic research orientation, is ideally suited to play a major R&D role in automation and robotics. The field is complex, and many different approaches need to be tried. Also, the technologies under discussion have a wide variety of applications and can be implemented at many levels of complexity and system integration. Ultimately, however, NASA will have the responsibility to provide facilities for integration and validation of autonomous space systems.

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**Key Technologies for the 1990s:**

An AIA report - November 1987

Composite Materials
VLSIC
Software development
Propulsion systems
Advanced sensors
Optical information processing
Artificial intelligence
Unreliable electronics

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NASA OAET AR1-32
History may judge artificial intelligence (AI) to be the most pivotal technology of this century. The success of many U.S. efforts is dependent upon computers that evaluate complex situations; therefore, the progress of AI development is crucial.

This advanced technology is concerned with complicated data processing problems and the development of problem-solving capabilities that elaborate on a model of human intelligence. AI covers a number of computer-based activities, one of the most common being the design of "expert" systems. Traditional computing techniques required hours of laborious programming to load a database with all possible solutions to each problem. In today's expert systems, computers use selected knowledge from one or more human experts to solve problems in much the same way as a human might. The only drawback is that such a system "learns" from new human input. Future AI systems will be capable of machine learning; their database will be continuously updated by the outcome of their own problem-solving operations.

The impact of AI technology on both military and civilian aerospace systems will be considerable. Human productivity will be increased, system performance and reliability will be improved and life cycle costs will be reduced. By the turn of the century, applications of AI are expected to revolutionize a variety of aerospace products, as well as the way in which those products are manufactured.

Applications of AI technology are heavily dependent on the availability of other newly emerging key technologies, such as advanced computer software.

AI will also be easier to implement with further development of computer hardware, very large-scale integrated circuitry and optical information processing. We need to encourage further advances in both computing hardware and theory, as well as develop demonstrators to illustrate AI applicability as the technology moves from theory to practice. Despite strong challenges from the Soviets and the Japanese, the United States still enjoys a lead in this technology, but without focused attention this lead will undoubtedly disappear.

### Advancement Inhibitors

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ARTIFICIAL INTELLIGENCE

RECOMMENDATIONS

- Place more emphasis on relevant, real demonstrators to encourage acceptance by system developers and enable AI to become specific in real systems.

- Encourage AI content in selected systems, as with automation and robotics, for space station.

- Expand government-sponsored industry internship programs for university faculty members on sabbatical.

- Using the Software Engineering Institute as model, organize similar efforts to encourage communication between AI, data-based management systems and software engineering technologies.

MAJOR BENEFITS

Key Technologies for the 1990s:
an AIA report - November 1987

"History may judge artificial intelligence to be the most pivotal technology of this century."

"By the turn of the century, applications of AI are expected to revolutionize a variety of aerospace products, as well as the way in which those products are manufactured."

PAYOFFS:
- Faster, more reliable information gathering and processing
- Improved performance for man-machine systems
- Greater mission flexibility and reliability
- Increased adaptability means longer life for inaccessible systems

RECOMMENDATIONS:
- Relevant real demonstrations to encourage acceptance
- Encourage AI in selected systems (eg for Space Station)
- Gov't sponsored industry sabbaticals for academicians
- Encourage communications between AI, data-based management systems and software engineering technologies
AUGUSTINE REPORT

RECOMMENDATIONS
- MISSION TO PLANET EARTH
  - info from EOS near 10 trillion bits of data per day, or about one Library of Congress per day (note: role for AI)
- MISSION FROM PLANET EARTH
  - "...exploration will be a continuum of robotic missions preceding the presence of man..."
- BASED ON:
  - NEW SPACE INFRASTRUCTURE
  - TECHNOLOGY BASE MUST BE REPLISHED
  - HI-CONFIDENCE, REASONABLE RISK TRANSPORTATION
  - INTERNATIONAL COOPERATION TO BROADEN OPPORTUNITIES
  - INSISTENCE ON EXCELLENCE
  - ANTICIPATE & MANAGE RISK (note: role for AI)
    - (remember Charles Perrow's book, Normal Accidents)
  - THREEFOLD INCREASE IN TECHNOLOGY FUNDS

RECOMMENDATION #7: That technology be pursued which will enable a permanent, possibly man-tended outpost to be established on the Moon for the purposes of exploration and for the development of the experience base required for the eventual human exploration of Mars. That NASA should initiate studies of robotic precursor missions and lunar outposts.

AUGUSTINE REPORT - Items on NASA Infrastructure: A&R implications

SYSTEMS ENGINEERING EXPERTISE
- "...enhancing cost estimating capabilities, margins for increasing cost, schedule and performance, and strengthen systems engineering."

ROLE OF UNIVERSITIES
- "We urge that universities, other institutions, and their investigator teams be used increasingly as "prime" contractors for space research instruments and projects."

DATA ANALYSIS
- "Research support activities, such as mission operations and data analysis programs, as well as many portions of the advanced technology development program, represent the life blood of civil space research."
- "The information to be gathered from EOS could approach 10 trillion bits of information - about one Library of Congress - per day."

PROCURMENT - Requires inordinate amount of time
AUGUSTINE REPORT -
Items on NASA Infrastructure:
A&R implications

HUMAN FRAILTY - 400,000 people at 20,000 involved in Apollo design

CONTINUING OPS COSTS - "...large complex space systems such as
the Shuttle and the Space Station that are or will be largely driven by
operational issues - turnaround time between flights, manifesting,
retrofitting of design changes for safety, cost or payload capability
purposes, logistics, training of basic and science crew members, ..."

TRAINING - Problems of getting, training, and keeping skilled workforce,
and of using lesser qualified people when appropriate to save money.

ROLE OF CODE R - "In particular we believe that technology which may
have generic applicability should be developed under the auspices of
the Associate Administrator responsible for advanced technology."

PERSONNEL - NASA has a bimodal age distribution, causing a problem
for future senior management selection.

NASA CENTERS - consolidate & eliminate overlap in areas of excellence

SSTAC Review of OAET AI Program
Sept. 1990 at ARC

Code RC's AI program presentations made by
- Peter Friedland, ARC
- David Atkinson, JPL
- Troy Heindel, JSC

SSTAC stated: This AI R&D program should be used as a model for
Code R's technology programs, noting
- strong internal program put together in short timeframe
- well connected with user community within NASA
- well connected with academic and industry AI community
- excellent mix of technology development and application
Exploration "Synthesis Report"
Stafford Committee (6-91)

Recommended four options, all involving rovers

1. MARS EXPLORATION
   - 2003: surface rover on Mars

2. SCIENCE EMPHASIS FOR MOON AND MARS
   - 2001: robotic lunar network
   - 2003: first Mars rover

3. PERMANENT MOON BASE WITH MARS EXPLORATION
   - 2002: robotic lunar rover

4. SPACE RESOURCE UTILIZATION
   - 2001: robotic lunar rover
OAET Artificial Intelligence Program
Integrated Technology Plan External Review

Presented by
Dr. Peter Friedland
Ames Research Center

June 26, 1991

Outline

• AI Program Philosophy
• NASA Center Roles
• Mission Objectives / Research Themes
• Case Studies
  - RTDS (Real-Time Data Systems)--JSC
  - SHARP (Spacecraft Health Automated Reasoning Prototype)--JPL
  - STS Orbiter Scheduling--ARC/KSC
  - AutoClass--ARC
  - PI-in-a-Box--ARC/MIT
  - How Things Work--Stanford
• Measures of Success
• Short Term (FY 1992) AI Program Growth
• Long Term Program Growth
Roles

• Ames: Fundamental Research, Variety of Applications
• Goddard: Applications to Unmanned Earth Orbital Missions
• Johnson: Shuttle Mission Control Applications, Research on Human Interface Issues
• JPL: Applications to Planetary Missions, Research in Scheduling and Sensor Modeling
• Kennedy: Shuttle Processing and Launch Applications
• Lewis: Applications to Electrical Power
• Marshall: Applications to Power and Propulsion

Research Themes

• Major Thrusts in:

  • Planning
    • Combinatoric, Constraint-Based Scheduling
    • "Anytime" Re-Scheduling
    • Multi-Agent Planning
    • Reactive Planning (Intelligent Agents)

  • Learning
    • Data Analysis and Classification
    • Theory Formation
    • Learning Architectures
    • Automatic Improvement in Problem-Solving

  • Design of and Reasoning about Large-Scale Physical Systems
    • Knowledge Acquisition during Design
    • Model-Building and Simulation
    • Knowledge Compilation
    • Symbolic Control
Goals

- Increase the quality of flight decision making
- Reduce/enhance flight controller training time
- Serve as a near-operations technology test-bed
REAL TIME DATA SYSTEM (RTDS)

- FEB 89 - STS-29 RTDS EXPANDED TO INCLUDE:
  - TIRE PRESSURE AUTOMATED MONITORING
    - PREVIOUSLY REQUIRED FULL TIME PERSON TO ACQUIRE DATA, COMPENSATE FOR TEMPERATURE, CONVERT TO STANDARD PRES AND PLOT (TASK AUTOMATION)
  - VISUALIZATION OF FLIGHT INSTRUMENTS (TASK AUTOMATION)
  - ASCENT GNC MONITORING - (TASK AUTOMATION)
  - INSTALLED MONITORS IN SOME CONSOLES REPLACING MAINFRAME DISPLAY UNITS
  - NETWORK INSTALLED FOR DISTRIBUTING SOFTWARE AND REAL TIME DATA

REAL TIME DATA SYSTEM (RTDS) UPGRADE PARADIGMS

TRADITIONAL

OLD SYSTEM Fri PM WEEKEND NEW SYSTEM SHAKEDOWN OPERATIONAL USE

FROM DEVELOPMENT

RTDS APPROACH

OLD SYSTEM MONTHS OPERATIONAL USE GRADUAL PHASEOUT

SHAKEDOWN MATURITY APPLICATIONS

LESSONS LEARNED NEW SYSTEM OPERATIONAL USE NEW SYSTEM

AR2-5
Technology Testbed (1992)

- The Procedural Reasoning System is a promising expert system software tool developed by Stanford Research Institute (SRI) in cooperation with ARC

- PRS will be interfaced with real-time shuttle telemetry from RTDS and evaluated during simulations and missions

- ARC LAN-Link to RTDS
  - Provide real-time data feed to AI researchers at ARC
SHARP PROGRESS

<table>
<thead>
<tr>
<th>Year</th>
<th>Evaluation Prototype</th>
<th>Reusable Kernel</th>
<th>Pilot Installation</th>
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<tr>
<td>1987</td>
<td>Shallow Diagnosis</td>
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<td>1991</td>
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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
CONSTRAINT-BASED SCHEDULING

- Expected to reduce ground operations time and cost per launch by streamlining and optimizing operations.
- Supports dynamic rescheduling in response to resource conflicts, operational problems, and other unexpected conditions.
- Provides operations personnel with an on-line "window" to schedules that are in-process, projected or completed.

Project Roles

ARC - Overall project management and system development.

LAIC - System development and LSOC support.

LSOC - Knowledge engineering, user support.
    (More system development after Mike D. transfers.)

KSC - KSC advocacy (the mole) and administration of Lockheed funds.
ALTERNATIVE SEARCH STRATEGIES: COMPARISON

TRADITIONAL — SYSTEMATIC BACKTRACKING

- GUARANTEED TO TERMINATE
  - INTUITIVE
  - EXHAUSTIVELY TESTED

ITERATIVE IMPROVEMENT — SIMULATED ANNEALING

- SIGNIFICANT PERFORMANCE IMPROVEMENT
  - "ANYTIME ALGORITHM"
  - INHERENTLY PARALLEL — CONNECTION MACHINE
  - MORE AMENABLE TO OVERCONSTRAINED PROBLEMS

SYSTEM ARCHITECTURE
Bayesian Learning

Goals: Development and application of Bayesian data analysis techniques to classification of large-scale, potentially noisy NASA databases.

Project Leader: Peter Cheeseman

Inhouse Effort: 5.5 FTE

Characterization: Basic and Applied Research, Tool Development

Domain Applicability: IRAS Data, CalSpace Cloud Data, LandSat Data

Start Date: 10/86

Projected Length: Indefinite

Fund Source: OAET AI Program

Machine Learning

Knowledge Intensive
- Strong prior theory
- One (or few) examples
- Verification by proof
- Learned concept must be useful

EBG

Knowledge Weak
- Weak prior model
- Many examples required
- Cannot prove theory
- Learned concept reflects intrinsic structure

Model Discovery

Markov Models

Classification Models

Series Prediction

Supervised

Unsupervised
The spectra show two closely related IRAS classes with peaks at 9.7 and 10.0 microns. This discrimination was achieved by considering all channels of each spectrum. AutoClass currently has no model of spectral continuity. The same results would be found if the channels were randomly reordered.

The galactic location data, not used in the classification, tends to confirm that the classification represents real differences in the sources.

FUTURE APPLICATIONS

Short Term (1-3 Years)

- Improvements to Autoclass
- Hidden Markov Models - speech, trend analysis, weather prediction
- Time series analysis - (e.g. SME data)
- Learning expert systems from data

Long Term (3-10 Years)

- Totally automatic data analysis/model discovery
- Integrates symbolic AI methods with statistical (numerical) approaches
"PI-in-a-box" as an Astronaut Science Advisor

GOALS:
• Monitor data quality and help diagnose problems with equipment when experimental data is erratic or poor
• Suggest protocol changes that would result in better utilization of remaining time
• Capture, reduce, and archive experimental data
• Identify and permit investigation of "interesting" data

Project Team

Laurence R. Young
(PI)
MIT

Silvano P. Colombano
Michael Compton
Richard Frainier
Irv Statler
NASA-Ames

Jurine Adolf
Tina Holden
Lockheed/JSC

Nicolas Groleau
Peter Szolovits
MIT
**Protocol Manager Screen: New Proposed Protocol**

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Support of SLS-1 Mission

- **Pre-flight baseline data collection:**
  - system used to collect and analyze data from Vestibular Dome experiment in the Baseline Data Collection Facility at JSC on L-150, L-75, L-45, L-30, and L-15 sessions
- **Ground support during flight experiment:**
  - system used in the Science Monitoring Area at JSC to collect and analyze in-flight data from the Dome experiment downlinked from Spacelab
- **Post-flight data collection:**
  - system in use at Dryden to collect and analyze data from the Dome experiment on R+0, R+1, R+2, R+4, R+7, and R+10 sessions

Plans for Support of SLS-2 Mission

- **In-flight use of system by crew**
  - system to be re-hosted on flight-qualified hardware and used by astronauts on orbit during SLS-2 mission (currently scheduled for May, 1993)
- **Pre-flight and post-flight data collection**
  - system to be used for collection and analysis of Dome data during baseline data collection sessions before and after the mission
Capabilities of a Human Expert

- Expertise in a speciality area
- General competence in a domain
- Common sense ability in all areas

The How Things Work Project

- Objectives
  - Develop systems that perform intelligently in a broad subject area
    - Have multiple areas of specialized expertise
    - Use general knowledge about a subject area
  - Develop knowledge reuse technology and infrastructure
    - Knowledge base translation and integration tools
    - Libraries of reusable knowledge bases

- Strategy
  - Focus on –
    - Knowledge about engineered devices
    - Support of device design, manufacturing, and maintenance
Measures of Success

- NASA Mission Utility:
  - Significant Operational Use in Shuttle Mission Control Center at JSC and Deep Space Mission Control at JPL. Systems Accepted as Standards for Control Center Upgrades
  - AI Program-Developed Scheduling Technology in Use for Shuttle Orbiter Processing at KSC
  - Future Mission Testbed Use at GSFC, LeRC, and MSFC
  - Utilization of Data Analysis Tools at Ames and JPL

- AI Research Contributions:
  - Major Impact in Publications. From Ames Internal Program Alone 5 AAAI-90 Papers (a New Record for a non-University) and 7 IJCAI-91 Papers (Also a New Record). Over 80 Peer-Reviewed Publications in Major Journals and Conferences in both 1990 and 1991 from the Program as a Whole
  - NASA Scientists Serving as Journal Editors, Editorial Board Members, and AAAI/IJCAI Program Committee Members on a Routine Basis

Long Term Growth Plans

- Movement of Fundamental Research Components into Base R&T Program

- Potential Addition of Natural Language Research Work to the Base Program (Particularly as Applied to Database Management)

- Considerable Expansion of External Research Projects in Academia and Industry

- More Spacecraft Applications Work (Perhaps to JPL Discovery Missions and/or Goddard Explorer Missions)

- EOS Science and Mission Control Applications

- Movement into the Training Infrastructure
ILLUSTRATIVE TECHNICAL HIGHLIGHTS
OF THE
NASA TELEROBOTICS PROGRAM

PRESENTED TO

THE INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM MEETING

JUNE 24 - 28, 1991
WASHINGTON, D.C.

BY

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THIS TALK IS INTENDED TO PRESENT TECHNICAL
R&D ACCOMPLISHMENTS OF JPL

1. THE PRESENTATION WAS CHOSEN AS REPRESENTATIVE OF THE BROADER NASA TELEROBOTICS PROGRAM.
   - INTIMATE FAMILIARITY OF TRIWG COCHAIR
   - WORK CONDUCTED BY LEAD CENTER
   - LIMITED TIME AVAILABLE

2. THERE ARE MAJOR ELEMENTS OF THE TELEROBOTICS R&D PROGRAM NOT DESCRIBED HERE
   - OTHER MAJOR NASA CENTERS
   - LEADING UNIVERSITIES AND INDUSTRIES CONDUCTING IMPORTANT AND EXCITING R&D
DESIRED CAPABILITY

- THE ABILITY TO RELIABLY AND EFFICIENTLY PERFORM COMPLEX Telerobot TASKS
  - ORU REPLACEMENT
  - FLUID SUPPLY RECHARGING
  - SURFACE CLEANING
  - RADIATOR PANEL REPLACEMENT
  - EXPLORATION AND SAMPLE ACQUISITION
  - ASSEMBLY OF LARGE STRUCTURES
  - RUN CABLEING

- IN A CLUTTERED, NON-STATIC ENVIRONMENT, WHERE OBJECTS OF INTEREST MAY BE OCCLUDED

- IN THE PRESENCE OF A RANDOMLY VARIABLE TIME DELAY BETWEEN REMOTE AND LOCAL SITES

- WHERE COMMUNICATIONS BANDWIDTH AVAILABLE IS LIMITED ON BOTH UP AND DOWNLINK

ALTERNATIVE CONTROL MODES

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<td>• COMPUTER-ASSISTED OPERATOR CONTROL (E.G., HUMAN TASK</td>
<td>• PROCESS-LEVEL AUTONOMY (E.G., GRASP FIXTURE)</td>
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<td>• CUSTOM CUTTING/WELDING REPAIR OPERATIONS</td>
<td>• POLISHING HIGH-PRECISION SURFACES</td>
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AR3-2
Solar Maximum Satellite Repair

Satellite launched in 1980
Collected data on solar flare activity
Failure of Attitude Control Subsystem (ACS) after 9 months
NASA estimate - repair cost = $19m
- replacement cost = $77m

Astronauts on STS-13 performed repair operation
1st objective - ACS module replacement
2nd objective - more complicated MEB replacement
STS-13 crew trained for 1 year in neutral buoyancy
Successful satellite repair in 1984 - MEB replacement took 2 hours

JPL
ADVANCED TELEOPERATION
PARADIGM DEMONSTRATION/EVALUATION EXPERIMENT
SOLAR MAX REPAIR MISSION (SMRM)

MOTIVATION
- REALISTIC: IT HAPPENED AND WELL-DOCUMENTED
- CHALLENGING AND VERY RICH IN CAPABILITY REQUIREMENTS
  - THERMAL BLANKET REMOVAL
  - HINGE ATTACHMENT FOR ELECTRICAL PANEL
  - OPENING OF ELECTRICAL PANEL
  - REMOVAL OF ELECTRICAL CONNECTORS
  - RELINING OF CABLE BUNDLES
  - REPLACEMENT OF ELECTRICAL PANEL
  - SECURING PARTS AND CABLES
  - RE-PLUG ELECTRICAL CONNECTORS
  - CLOSING OF ELECTRICAL PANEL
  - REINSTATING THERMAL BLANKET
ADVANCED TELEOPERATION: 1990 HIGHLIGHTS SUMMARY

PREVIEW DISPLAYS
CALIBRATED TASK SET-UP
WORK UNDOABLE
ARMS COLLIDE
WORK DOABLE

NEW SMART HANDS
REMOTE
DUAL ARM
OVERLAY
FIBER OPTIC COMMUNICATION
CONTROL STATION

PREDICTIVE DISPLAYS
CALIBRATION
OVERLAY
PREDICTION

PREVIEW AND FORCE-REFLECTING GRAPHICS DISPLAYS

8-DOF AAI ARM GRAPHICS IMAGE AND DUAL-ARM SET-UP FOR SMSR TASK

FORCE INDICATING/REFLECTING CAPABILITY
NO CONTACT
CONTACT

AR3-4
ADVANCED TELEOPERATION, 1990
SIMULATED SOLAR MAX SATELLITE REPAIR TASKS
- Thermal blanket cutting
- Unbolting main electronic box panel
- Control station upgraded with displays
- Worksite upgraded with Multi-TV gantry system

SOLAR MAX SATELLITE REPAIR EXPERIMENTS

USE OF DIAGONAL CUTTERS FOR CUTTING PLASTIC TIE WRAPS OF WIRE BUNDLES

USE OF POWER SCREW DRIVER TO REMOVE CONNECTOR SCREWS
Experimental Task - Unbolting, Bolting

Move forward from start position to screw head

Start unbolting, withdraw tool as screw unbolts

After screw free of hole, move back to start position

Move back to screw hole

Bolt screw and move tool in as screw enters hole

Subject Training

Perform task until consistent
5 successive repetitions with std. dev. < 0.15 of mean

Experiment Design

Seven subjects
Seven control modes
Three repetitions of task in each mode
Total of 21 repetitions per subject - randomized

Data Collected
Slave position/orientation, interaction forces/torques
Gripper force, gripper position, task completion time
RESULTS: RELATIVE TO SELECTED TASK

POSITION CONTROL BETTER THAN RATE CONTROL
POSITION ERROR BASED FORCE REFLECTION BETTER THAN ALL OTHER POSITION CONTROL MODES
PURE POSITION CONTROL BETTER THAN PURE RATE CONTROL

OBSERVATION:

COMPLIANCE BETTER THAN FORCE REFLECTION
SUBJECTS PREFERRED POSITION CONTROL OVER RATE CONTROL

FORCE-REFLECTING EXOSKELETON
ANTHROPOMORPHIC TELEMANIPULATION
THE EXOSKELETON ALTERNATIVE

• QUESTION: HOW FAR CAN THE EXOSKELETON ALTERNATIVE TRULY PERFORM THE EVA-GLOVE RATED MANIPULATIVE ACTIVITIES WITHOUT CHANGING EVA TOOLS/PERIPHERALS OR WITHOUT ADDING NEW ONES TO THE EXISTING REPERTOIR? (155 TOOLS AS OF 1985)

• ANSWER: CARRY OUT EXOSKELETON EXPERIMENTS WITH REALISTIC EVA TOOLS ON REALISTIC EVA TASKS, IN COOPERATION WITH INTERESTED NASA CENTERS' PERSONNEL

**JUSTIFICATION**

- Several studies have indicated that inspection will be an important activity for Space Station Freedom:
  - SMR Blue Panel Report, June 12, 1990

- Use of telephones can reduce astronaut EVA time

- Database from this task will provide actual experimental data for more realistic estimates for the SSF inspection tasks

- This task will also show technology readiness and identify what new technologies are required for inspection tasks.

**REMOTE SURFACE INSPECTION**

**IDENTIFIED INSPECTION TASKS:**

- Inspection for truss strut damaged by micrometeoroids
- Inspection for visible cracks in structures
- Inspection for shield area damaged by micrometeoroids
- Inspection of thermal blanket, radiator, and solar panel damage by micrometeoroids and atomic oxygen
- ORU inspection (prior to and after installation)
- ORU System Diagnostics: SSRMS or SPDM power and data interfaces are used to perform ORU diagnostics
- Inspection of deployable mechanisms for incorrectly positioned latches, connectors, and other mechanical devices
- Inspection of the SSF-based Shuttle docking port before each docking
- Utility tray inspection: inspection of fluid and power lines
- Environmental monitoring: monitoring of magnetic fields, plasma fields, contaminants levels, and toxic gas concentration
- Close out a new process for certifying payloads
REMOTE SURFACE INSPECTION

LONG DURATION EXPOSURE FACILITY (LDEF) EXAMPLES:

(a) Solis array materials LDEF experiment

(b) Thermal blanket damaged by micrometeoroid and delamination

(c) Concentrically rings impact feature into white painted aluminum surface

AR3-10
REMOTE SURFACE INSPECTION

OPERATIONS SCENARIO:

- Remote Visual Inspection:
  - Damaged objects are placed on the mockup.
  - Operator is asked to locate damaged areas.
  - Operator uses the manipulator carried cameras and the controlled lights to identify damaged areas.
  - A simple test is performed to measure operator’s accuracy and time-to-completion.

- Automated Inspection:
  - Arm moves based on a prerecorded trajectory while the automated inspection module performs inspection.
  - This requires synchronization between manipulator control and automated inspection module.
  - Inspection is done by comparing previously recorded with present data.
  - Automated inspection technique is based on eliminating or minimizing effect of ambient lighting.
  - System responds with ‘FOUND DAMAGE, NO DAMAGE, or DON’T KNOW’
REMOTE SURFACE INSPECTION

MANIPULATOR CONTROL

- A redundant 7DOF robotic arm is used for dexterous placement of sensors for surface inspection.

- A novel configuration control methodology developed at JPL is implemented for task-based resolution of redundancy.

- Using space shuttle-type joysticks, operator controls the endpoint of the arm while the arm posture/configuration is controlled automatically based on a priori selected task constraints.

- Currently developing supervisory teleoperation where arm collision with environment is avoided automatically based on a world model.
REMOTE SURFACE INSPECTION

Automated Flaw Detection

OBJECTIVE: Detection of flaws for simple but time-consuming inspections tasks

GENERAL APPROACH: Detection of changes between "before" and "after" images of a scene

TECHNICAL ISSUES:

- Earth orbit ambient light variations for "before" and "after" images
- Misregistration between the "before" and "after" images due to camera positioning repeatability which causes large differences in high contrast regions

TECHNICAL APPROACH:

- Subtract image of ambient lit surface from one lit by controlled lights and improve the results by averaging over many images
- Develop estimation techniques to correct for camera repositioning error
- Perform subtraction only in non-high contrast regions by means of image-masking
HAZARDOUS MATERIALS INCIDENTS — JPL

EXAMPLES:

- Sulfuric Acid Spill (Pallet of batteries dropped during delivery) — 1988, Level B (Proper equipment not available at time of incident).
- Hydrogen Fluoride Faulty Cylinder Regulator (Threatened Release) — Building 189, November 1989, Level C (Should have been Level A; proper equipment not available at time of incident).
- Anhydrous Ammonia Leak — Building 111, March 1990, Level B
- Propane Leak — Building 264, October 1990, Level C
- Sulfur Acid Spill — Cryogenics Dock, September 1990, Level B
- 111 Trichloroethane Spill — Building 111, September 1990, Level B
- Phosphine Leak (Faulty cylinder) Class A Poison/Toxic Gas — Building 302, November 1990, Level A (Storage in hydrogen created additional explosive danger).

STATISTICS:

- Incidents requiring Level B suitup — 1 incident/2 weeks (average)
- Oxygen Deficiency testing — 6 times/week (average)

APPROACH

- Involvement of experts in the detection and handling of hazardous materials:
  - JPL Occupational Safety Office (OSO)
  - JPL Fire Department and Emergency Response Team
  - JPL’s Lead Chemical Safety Engineer
  - JPL’s Principle Safety Coordinator
- Procurement of two identical vehicles:
  - Development of new system capabilities
  - Field testing, performance evaluation, and deployment on actual emergencies. (Operated by JPL’s Emergency Response Team)
- Identification of needed capabilities based on direct user inputs (e.g., transmit data signals from chemical sensors to operator, physically scan door seals with sensor probes, etc).
- Development and implementation of user specified capabilities.
- Transfer of in-house robotic technologies and expertise.
SYSTEM REQUIREMENTS — SPECIFIC

- Traverse 150-200 ft of pavement to building entrance.
- Transmit chemical sensor readings to vehicle control station (audio alarms, analog meters).
- Inspect exhaust vents for chemical emissions using cameras and chemical sensor probes.
- Scan door seals with sensor probes (1-2 inches away).
- Open and clear exterior door (Thumb Latch Type, Door Closer).
- Retrieve, manipulate, and stow various components (sensor probes, door key, door stops)
- Open Stop Room door (Knob w/Key).
- Inspect store room entrance prior to entry using cameras and chemical sensor probes (i.e., view around corners).
- Climb onto and later over 10 inch door sill.
- Visually scan and inspect chemical stores w/onboard lights (shelves ranging from 1-7 ft high).
- Navigate to decontamination site.
JPL
EMERGENCY RESPONSE ROBOTICS

VISUAL AND CHEMICAL SENSOR INSPECTION
PRIOR TO PHYSICAL ENTRY

HUMAN ENTRY TEAM

HAZBOT-II

AR3-16

HWS 2-89 (16)
USER EXPERIENCE & NEEDS

- Ability to safely enter confined spaces containing combustible vapors is critical to the acceptance of a robotic Emergency Response Vehicle.
- The input/output devices used in the operator interface, their configuration, and the manner in which they invoke actions make it awkward if not difficult to control the system’s manipulator and drive elements. Users seek an interface which is self-explanatory in terms of the actions it invokes.
- HAZMAT personnel typically have little, if any, prior experience in operating complex multi-degree of freedom systems. Hence, a viable system must incorporate sensors and controls aimed at reducing the operator’s need to perform complex spatial reasoning.
- Positioning sensor probes at strategic locations such as door seams and other similar tasks is complicated by the operator’s limited ability to correctly perceive depth. Effective means for perceiving depth are required.
- Existing systems are unable to perform basic operations essential to HAZMAT response, such as turning valves off, given the lack of tooling and simple means for their storage and retrieval.
- Existing systems do not support and/or are unable to deploy chemical sensors commonly used in responding to Hazardous Materials incidents.

THERE HAVE BEEN SIGNIFICANT AND WIDE-RANGING PROGRAM ACCOMPLISHMENTS

EXAMPLES

1. ASSEMBLY OF A TETRAHEDRAL TRUSS STRUCTURE WITH APPROXIMATELY 100 ELEMENTS (LaRC)
2. TWO TWO-ARMED FREE-FLYING ROBOTS COOPERATIVELY MANIPULATING A COMMON OBJECT (STANFORD UNIVERSITY)
3. FAULT-TOLERANT MANIPULATOR JOINT DEVELOPMENT (JSC)
4. NEUTRAL BUOYANCY ASSEMBLY OF STRUCTURES AND SATELLITE SERVICING (UNIVERSITY OF MARYLAND)
5. SHUTTLE TILE INSPECTION AND REWATERPROOFING (KSC)
THERE ARE STILL MANY
TECHNICAL AND PROGRAMMATIC FRONTIERS

TECHNICAL:

(1) **SAFE AND ROBUST CONTROL OF MANIPULATOR/ENVIRONMENT INTERACTION**,
(e.g. COMPOUND MANIPULATORS, FAULT TOLERANCE)

(2) **MACHINE PERCEPTION IN REAL TIME**

(3) **HUMAN FACTORS CONSIDERATION (E.G. CAMERA POSITIONING, LIGHTING)**

(4) **DEVELOPMENT OF A LIBRARY OF MACRO SKILLS**

(5) **TELEROBOTICS/EVA INTEGRATION**

(6) **ERROR RECOVERY AND GRACEFUL DEGRADATION**


THERE ARE STILL MANY
TECHNICAL AND PROGRAMMATIC FRONTIERS (CONT'D)

PROGRAMMATIC

(1) **NEAR-TERM SYSTEM DEMONSTRATIONS ARE REQUIRED TO BUILD CONFIDENCE**
   (e.g. SPACECRAFT INTEGRATION AND TEST, PAYLOAD INSPECTION)

(2) **ROBUST PERFORMANCE IS PREREQUISITE TO ACCEPTANCE**
   (e.g. FLIGHT EXPERIMENTS, FAULT TOLERANCE, GRACEFUL DEGRADATION)

(3) **MAINTAIN A STRONG INFRASTRUCTURE**
   (SUITABLE BLEND OF BASIC AND APPLIED RESEARCH)

(4) **PARTICIPATE WITHIN THE INTERNATIONAL COMMUNITY WHERE APPROPRIATE**
   (e.g. EXCHANGE VISITS HAVE ALREADY BEGUN WITH JAPAN AND FRANCE)
Planetary Rover Program

June 26, 1991
SSTAC/ARTS External Review

Technology Challenges

- Missions: Mars Sample Return, Lunar Exploration, Mars Exploration
- Needs: Unmanned Science Rovers (Near-term)
  - Low (2-500Kg) vehicle mass
  - Semi-autonomous navigation
  - 100m-40Km traverse distances
  - SAAP payload compatibility
  - 1-year lifetime (minimum)
  - System autonomy
  - High mobility
Technology Challenges (con't)

- Missions: Lunar Outpost Placement, Remote Lunar Science, Lunar VLFA Construction
- Needs: Unmanned Lunar Rovers (Mid-term)
  - 5-year+ operational lifetime
  - Regolith manipulation capability
  - Advanced materials/tribology
  - 1000Km+ traverse per year
  - System Autonomy
  - Long-life mobility
  - CARD navigation

Planetary Rover Program

Technology Challenges (con't)

- Missions: Outpost Crew Transport, Regolith Mining, ISRU, Cargo Transport
- Needs: Manned Lunar/Mars Rovers (Far-term)
  - Mobile pressurized life support (ECLSS)
  - Advanced materials/tribology
  - Long-life mobility systems
  - 2-4 person crew support
  - Navigation aides

Planetary Rover Program
### Earliest Technology Needs Horizons

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<td>OSSA Strategic Plan</td>
<td>SEI Study</td>
<td>JSC Robotic Rover Report</td>
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(From Space Technology Long Range Plan)

### Planetary Rover Program

### Current State Of The Art - Technology

- **Navigation**
  - 100-meter SAN in 4 hours
  - 500-meter CARD
  - Remote teleoperated driving

- **Mobility**
  - Apollo LRV drive systems/wheels
  - Lab demos of walking machines
  - Lab demo of pantograph suspension

- **Operations Autonomy**
  - HST constraint propagation schedulers
  - Ground-based remote scheduling systems (Voyager)

- **Mobile Power**
  - Low power photovoltaics
  - Apollo LRV batteries
  - Voyager RTGs

Planetary Rover Program

AR4-3
Current State Of The Art - Systems

- Remote mining/trucking
- Remote ordinance disposal vehicles
- Battlefield survey/recon vehicles
- Apollo LRV
- T.M.I. clean-up vehicles

There are no operational systems in the United States which can compensate for Earth-Mars (or Earth-Lunar) time delays

Planetary Rover Program
Related Efforts

- DoE-Sandia: Contaminated site clean-up vehicles
- US Army-TACOM: Battlefield survey/recon vehicles
- DoD-DARPA: Autonomous Land Vehicle
- DoE-Idaho Falls: Contaminated site clean-up vehicles
- Martin-Marietta: Mars rover IR&D

Goals and Objectives

- Goal: Develop the technologies to enable robust, flexible and efficient vehicle systems for planetary surface operations.
  - Identify technologies which are required to enable robust, efficient and flexible planetary rover systems
  - Identify, using terrestrial experiments, the current capability of rovers to perform complete system-level tasks
  - Determine what increased capabilities are necessary and desirable for rovers to perform several tasks
  - Selectively develop these component technologies to determine their operational characteristics in a realistic environment
  - Demonstrate an integrated system designed to illuminate the impact of the new technology on overall system performance
Program Structure

Program Developments to Date

- Initial SAN
- Autonomous walking
- Task Control Architecture
- Active sensing perception system
- Local terrain mapper
- Generalized gait planner
- Structured light sample acquisition
- Composite terrain mapping
- Active leveling system
- Legged mobility mechanism design
- Fine powder SiGe electrode samples
- SiGe spark erosion apparatus
- Stereo correlation algorithms
- Terrain matching algorithms
- Global path planner
- Expectation generation system
- Execution monitoring system
- Path and monitoring planner
- Mobility analysis wheel model
- Ground-based sequencing simulator
- Design reference mission definition
- Piloted rover technology needs assessment
Program Schedule


100-meter SAN
Indoor autonomous walking in rough terrain
Sample collection task in 200-m test course with SAN, CARD, teleop
Micro-rover sample collection task
Robust self-contained autonomous walking with sampling
Behavior-controlled micro-rover sample collection task
Outdoor walking in rough terrain

Planetary Rover Program

Program Schedule (continued)


Extended sample collection task with dynamic replanning, continuous traverse, AOTF integration
Behavior-controlled micro-rover science instrument emplacement task
Extended outdoor autonomous walking
Lunar manned rover testbed development
Science instrument deployment task in extended field test
AMBLER II field testing

Planetary Rover Program
**Rover Funding Profile**

---

**Dollars In Millions**

- **FY 88 Guideline**
- **FY 89 Guideline**
- **FY 90 Guideline**
- **FY 91 Guideline**
- **FY 92 Baseline**

---

**Issues**

- No rover program in FY 92-97 baseline
- No operational or demonstrated rover systems which compensate for time delay
- Mission architectures still undefined for Lunar and Mars systems
- Reduced-funding of rover-supporting program elements
- Directed reduction of manned rover efforts
- Directed reduction of mining & construction rover efforts

---

**Planetary Rover Program**

AR4-8
NASA

PLANETARY ROVER

PROGRAM

ROGER BEDARD
JET PROPULSION LABORATORY

& DAVID LAVERY
NASA HQ/CODE RC

JUNE 26, 1991
SSTAC MEETING

OUTLINE

- GOALS
- BACKGROUND
- SCIENCE ROVER INTRODUCTION
  - OBJECTIVES AND LONG RANGE PLANNING
  - VISION
  - APPROACH
  - TECHNOLOGY NEEDS
- SCIENCE ROVER ACCOMPLISHMENTS
  - LEGGED LOCOMOTION AND AUTONOMOUS WALKING
  - WHEELED LOCOMOTION AND AUTONOMOUS NAVIGATION
  - MICRO AND MINIROVER TECHNOLOGY
- PILOTED ROVER ACCOMPLISHMENTS - TECHNOLOGY ASSESSMENT STUDY
- SUMMARY

ROVER PROGRAM INCLUDES:
- SCIENCE ROVERS
- PILOTED ROVERS
- CONSTRUCTION ROVERS

FOCUS OF THE ROVER PROGRAM AND THIS REVIEW IS THE SCIENCE ROVER
GOALS

TO DEVELOP, INTEGRATE AND VALIDATE THE TECHNOLOGY TO ENABLE MANNED AND UNMANNED ROVERS, ON BOTH LUNAR AND PLANETARY SURFACES, IN SUPPORT OF THE SPACE EXPLORATION THRUST

- UNMANNED SCIENCE (AND EXPLORATION) ROVERS
- PILOTED ROVERS
- CONSTRUCTION ROVERS (VEHICLES)

THE INITIAL FOCUS HAS BEEN ON PLANETARY ROVER MOBILITY AND NAVIGATION FOR EXPLORATION AND SCIENTIFIC INVESTIGATION

BACKGROUND

- UNMANNED SCIENCE ROVERS
  - LUNAKOD
  - MARS ROVER
- PILOTED ROVERS
  - APOLLO LUNAR ROVER VEHICLE (LRV)
  - SEI UNPRESSURIZED ROVER
  - SEI PRESSURIZED ROVER
- CONSTRUCTION ROVERS
  - SEI PAYLOAD UNLOADER
  - SEI MINING EXCAVATOR/LOADER
GOALS

BACKGROUND

SCIENCE ROVER INTRODUCTION
  - OBJECTIVES AND LONG RANGE PLANNING
  - VISION
  - APPROACH
  - TECHNOLOGY NEEDS

SCIENCE ROVER ACCOMPLISHMENTS
  - LEGGED LOCOMOTION AND AUTONOMOUS WALKING
  - WHEELED LOCOMOTION AND AUTONOMOUS NAVIGATION
  - MICRO AND MINIROVER TECHNOLOGY

PILOTED ROVER ACCOMPLISHMENTS - TECHNOLOGY ASSESSMENT STUDY

SUMMARY

ROVER PROGRAM INCLUDES:
  - SCIENCE ROVERS
  - PILOTED ROVERS
  - CONSTRUCTION ROVERS

FOCUS OF THE ROVER PROGRAM AND THIS REVIEW IS THE SCIENCE ROVER

PLANETARY SURFACE SCIENCE MISSIONS ARE INEVITABLE

'ROVING' ALLOWS WIDE AREA SURFACE SCIENCE AS DEMONSTRATED BY APOLLO LRV AND SOVIET LUNAKHOD

OBJECTIVE

TO DEVELOP REMOTELY PILOTED SCIENCE ROVERS, COVERING A SIZE RANGE OF 1 TO 1000 KG, THAT CAN:

- PERFORM SCIENTIFIC EXPLORATION
- IDENTIFY, ACQUIRE, ANALYZE AND PRESERVE SCIENCE SAMPLES
- DEPLOY SCIENCE INSTRUMENTS
TEST AND EVALUATION OF BREADBOARD SCIENCE ROVER OPERATIONS IN RELEVANT EARTH TEST ENVIRONMENTS

- Science Rover Testing at JPL Arroyo, Edwards and Death Valley
- Remote Mission Control

- SHOW SPACE SCIENCE COMMUNITY THE CAPABILITY OF THE SCIENCE ROVER SYSTEMS
- BUILD A DATABASE SO DESIGNERS AND SCIENTISTS CAN UNDERSTAND THE IMPORTANT MISSION TRADEOFFS

THE APPROACH

INVESTIGATE ROVER TECHNOLOGY OPTIONS
AND VALIDATE SYSTEM TASK CAPABILITY
IN RELEVANT EARTH TEST ENVIRONMENTS

- Different Configurations
- Different Components
- Various Sizes
- Scientific Exploration
- Surface & Subsurface Sample Acquisition, Analysis and Preservation
- Science Instrument Emplacement
- At Various Levels of Human Control
- With Various Levels of Time Delay (from 0 to 40 minutes)

JPL Arroyo, Edwards or Death Valley
**NASA OAET TECHNOLOGY NEEDS**

**KEY TECHNOLOGY NEEDS INCLUDE:**
- Minaturization and micro/mini rovers
- Low power, low mass, high mobility vehicle
- Passive and active sensing and perception
- Path planning and behavior control
- Computer aided remote driving navigation - Variable time delay
- Coordination of mobility and manipulation
- Mission operations
- Systems integration and science task demonstration

**SCIENCE ROVER RESEARCH AND TECHNOLOGY MUST ADVANCE THE STATE OF TECHNOLOGY ALONG MANY DIMENSION, INCLUDING:**
- Size
- Degree of autonomy
- Science system task capability
- Operational Limits (eg. day/night vs day only)
- Reliability
- Safety Limits (eg. types of detectable hazards such as duricrust, pits, etc)
- Configuration
- Adaptability
- Robustness

**NASA OAET OUTLINE**

- **GOALS**
- **BACKGROUND**
- **SCIENCE ROVER INTRODUCTION**
  - OBJECTIVES AND LONG RANGE PLANNING
  - VISION
  - APPROACH
  - TECHNOLOGY NEEDS
- **SCIENCE ROVER ACCOMPLISHMENTS**
  - LEGGED LOCOMOTION AND AUTONOMOUS WALKING
  - WHEELED LOCOMOTION AND AUTONOMOUS NAVIGATION
  - MICRO AND MINIROVER TECHNOLOGY
- **PILOTED ROVER ACCOMPLISHMENTS - TECHNOLOGY ASSESSMENT STUDY**
- **SUMMARY**

ROVER PROGRAM INCLUDES:
- SCIENCE ROVERS
- PILOTED ROVERS
- CONSTRUCTION ROVERS

FOCUS OF THE ROVER PROGRAM AND THIS REVIEW IS THE SCIENCE ROVER

AR5-5
CMU LEGGED VEHICLE MOBILITY AND NAVIGATION

**OBJECTIVES**

DEVELOP LEGGED LOCOMOTION ENABLING SUPERIOR ROUGH TERRAIN TRAVERSABILITY (COMARED TO WHEELED VEHICLES) WHILE ACHIEVING PRACTICAL POWER EFFICIENCIES

DEVELOP AUTONOMOUS NAVIGATION FOR AMBLER

**PARTICIPANTS AND FACILITIES**

**PARTICIPANTS**
- CARNEGIE MELLON UNIVERSITY

**FACILITIES**
- SINGLE LEG TESTBED
- SIX LEGGED AMBLER
- PLANETARY ROVER LABORATORY

**SCHEDULE AND FUNDING**

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**CMU KEY ACCOMPLISHMENTS**

(1988 THROUGH JUNE, 1991)

- FORMULATED A SIX LEGGED ROVER VEHICLE CONCEPT
- IMPLEMENTED A SINGLE LEG SYSTEM CAPABLE OF WALKING THROUGH ROUGH TERRAIN
  - INTEGRATES SENSING, PERCEPTION, PLANNING AND EXECUTION
  - PERFORMED EXTENSIVE TESTING LOGGING 100's OF METERS IN ROUGH TERRAIN
- DESIGNED AND BUILT THE SIX-LEGGED 'AMBLER' VEHICLE
  - COMPLETED ASSEMBLY IN DEC. 1989
  - ACHIEVED FIRST INDOOR WALKING IN MAY, 1990
- INTEGRATED SENSING, PERCEPTION, PLANNING AND EXECUTION AND ACHIEVED TETHERED AUTONOMOUS INDOOR WALKING IN DEC 1990
- CURRENTLY MIGRATING THE ELECTRONICS AND COMPUTERS ON BOARD THE AMBLER TO REDUCE THE SIZE OF THE TETHER
### OBJECTIVE

Develop remotely piloted science rovers, covering a size ranging from 1 to 1000 kg, that can:
- Perform scientific exploration
- Identify, acquire, analyze and preserve science samples
- Deploy science instruments

### PARTICIPANTS AND FACILITIES

#### PARTICIPANTS
- JPL ROBOTICS & AUTOMATION SYSTEMS
- JPL ADVANCED INFORMATION SYSTEMS
- JPL SPACE MICROELECTRONIC DEVICE TECHNOLOGY SECTION
- JPL MECH SYSTEMS DEV SECTION
- JPL MISSION PROFILE & SEQUENCING SEC
- MIT AI LABORATORY

#### FACILITIES
- JPL ROBOTICS LABORATORY
- U.S. ARMY DISPLAY & CONTROL STATION

### SCHEDULE AND FUNDING

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<th>Micro Rover Sample Acquisition</th>
<th>Deploy Science Instruments</th>
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### JPL KEY ACCOMPLISHMENTS

(1989 THROUGH JUNE 1991)

- DEVELOPED NAVIGATION TESTBED VEHICLE ‘ROBBY’, SEMI-AUTONOMOUS NAVIGATION (SAN) TECHNOLOGY AND ACHIEVED CONTINUOUS 100 METER SAN TRAVERSE IN ROUGH, NATURAL Terrain
- DEVELOPED A NEW WHEELED VEHICLE MOBILITY CONCEPT THAT HAS ACHIEVED TWICE THE BUMP PERFORMANCE OF PREVIOUS TECHNOLOGY
- DEVELOPED A ROVER MISSION OPERATIONS SIMULATION CAPABILITY, PERFORMED TWO SCENARIOS, A SAMPLING SCENARIO AND A SUB-SURFACE WATER DISCOVERY SCENARIO AND DEVELOPED A MISSION OPERATIONS COMMAND LANGUAGE
- ACHIEVED AN INDOOR EXPLORATION AND SAMPLE GATHERING DEMONSTRATING SIMPLE BUT ROBUST MICRO-ROVER BEHAVIOR
ROVER PROGRAM INCLUDES:
• SCIENCE ROVERS
• PILOTED ROVERS
• CONSTRUCTION ROVERS

FOCUS OF THE ROVER PROGRAM AND THIS REVIEW IS THE SCIENCE ROVER.

GOALS
BACKGROUND
SCIENCE ROVER INTRODUCTION
• OBJECTIVES AND LONG RANGE PLANNING
• VISION
• APPROACH
• TECHNOLOGY NEEDS
SCIENCE ROVER ACCOMPLISHMENTS
• LEGGED LOCOMOTION AND AUTONOMOUS WALKING
• WHEELED LOCOMOTION AND AUTONOMOUS NAVIGATION
• MICRO AND MINIROVER TECHNOLOGY
PILOTED ROVER ACCOMPLISHMENTS - TECHNOLOGY ASSESSMENT STUDY
SUMMARY

PILOTED ROVER TECH ASSESSMENT STUDY
INTRODUCTION
• Performed by Boeing under contract to MSFC
• Purpose to determine technology advancements required for a utility rover in support of establishing a lunar surface habitation facility and exploration base
• Two types of piloted rovers; a light unpressurized vehicle for short range (local outpost) use and a medium range pressurized exploration vehicle

SUMMARY OF TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

- Wheels
- Drive Systems
- Lubricants and Seals
- Shocks/Dampers
- Implements
- ECLSS
- Electrical Power
- Thermal Control
- Man systems
- Structures and Mechanisms
- Radiation Protection
- Navigation
- Communications
- EVA
- Finishes and Coating
- System Integration
**OUTLINE**

- GOALS
- BACKGROUND
- SCIENCE ROVER INTRODUCTION
  - OBJECTIVES AND LONG RANGE PLANNING
  - VISION
  - APPROACH
  - TECHNOLOGY NEEDS
- SCIENCE ROVER ACCOMPLISHMENTS
  - LEGGED LOCOMOTION AND AUTONOMOUS WALKING
  - WHEELED LOCOMOTION AND AUTONOMOUS NAVIGATION
  - MICRO AND MINIROVER TECHNOLOGY
- PILOTED ROVER ACCOMPLISHMENTS - TECHNOLOGY ASSESSMENT STUDY
- SUMMARY

**SUMMARY**

- The Planetary Rover Program is Well Advocated and Highly Regarded
  - Rover and microrover technologies are "of primary importance... to the Solar System Exploration Division, Code SL" per Wes Huntress letter to Greg Reck dated Jan 30, 1991
  - "From the science standpoint, future planetary missions (following the current flybys and orbiters) will require landers and rovers" per Dr. Stone (JPL Director) to A. Aldrich (NASA Code R AA) dated Feb 8, 1991
  - "Planetary Rover teams at JPL and CMU have made significant progress" per Aviation Week, March 18, 1991 quote from John Mankins, Code RS ETP Program Manager

- The Planetary Rover Program is planning exciting new accomplishments for FY 92 including:
  - A Robby Science sample acquisition experiment
  - Outdoor Ambler operation
  - Microrover and minirover sample acquisition experiments
- ROVER TECHNOLOGY PLANS ARE WELL COORDINATED WITH POTENTIAL ROVER USERS
  - JSC PLANET SURFACE SYSTEMS (LED BY BARNEY ROBERTS AND JOHN CONNOLLY)
  - OSSA ADVANCED MISSION STUDIES (LED BY WES HUNTRESS WITH ERWIN SCHMERLING BEING THE ROVER POC)
  - JPL FLIGHT PROJECT OFFICE ADVANCED MISSION STUDIES (LED BY JOHN BECKMAN)
- ROVER SUPPORTS TWO MAJOR NASA OAET THRUSTS
  - EXPLORATION
  - SCIENCE
- JPL AND CMU ROVER WORK RECEIVING MEDIA ATTENTION
  - NUMEROUS TELEVISION NEWSCLIPS
  - NUMEROUS MAGAZINE AND NEWSPAPER ARTICLES
- CONCERNED ABOUT THE FATE OF THE ROVER PROGRAM, THE ROVER TEAM AND THE ROVER EQUIPMENT DUE TO GREATLY REDUCED QR LACK OF FY 92 FUNDING
BRIEFING TO THE SPACE SYSTEMS TECHNOLOGY ADVISORY COMMITTEE ON

SCIENCE SENSOR TECHNOLOGY

FOR THE INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

JUNE 26, 1991

DR. MARTIN SOKOLOSKI

OFFICE of AERONAUTICS, EXPLORATION and TECHNOLOGY (CODE R)
SCIENCE SENSING TECHNOLOGY PROGRAM

OBJECTIVE:
Provide the sensing system technology to enable the required science sensing instrumentation necessary for the space science and applications programs consisting of missions studying:

- The planet Earth
- The solar - space physics
- Other planets & planetary systems
- The universe - astrophysics
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

OSSA TECHNOLOGY NEEDS

NEAR TERM NEED

HIGHEST PRIORITY

Sub-mm & Water Sensing
Long-Wave Instruments
Sensing
High Energy Detectors
Sensor Readout Electronics
Sensor Access Technology
Extenuating Influence Technology
Extreme Ultra-Radiation and Pulsed Radiation

High Frame Rate Res. Video/Color Cameras
2 x 2 Meters 100 X 1000 1000
Sensor Arrays
Automatic Binocular Analysis
Radiation Hardened Parts Detectors
Large Volume Energy Detectors
Real Time Environmental Control
Space Qualified Radiation Detectors
Fixed Detections

Mid-Highest Priority

Descend Imaging Mk 17 G Min Camera
Spacecraft Interferometry
Lidar High Resolution Terrestrial
Mini Spacecraft Subsystems
Real Time Navigation
Spacecraft Interface Characterization
Large Light Scattering
High Temperature Meters for Tumors
Flow, Reaction Gas Chromatographs
Alpha, Gamma Technology

MID TERM NEED

MIDTERM NEED

Long Life Stable Tunable Lasers
Seeker Probe Mercury Dimeric Thermal Probe
High Velocity Rare Earth Laser Storage
Temperature Specific Technology

Auto Sequencing & Command Generation
Auto S/C Monitoring & Fault Recovery
2 M TMT Optical Communications
Telescience Telemetry & Commanding
Improved S/C Output Processing (EMU)
Combustion Devices
Plasma Wave Antenna/Thermal

Regenerative Life Support
Thermal Control System
Non-Contact Temp. Measurement
3-D Packaging for Mill Solid State Chassis
Micro-pack Decontamination Methods
Animal and Plant Reproduction
Special Purpose Electrode Simulators
Space Station Sensor Delivery & Return Capability

FAR TERM NEED

Structures Large Composite Reinforced Composites
Precision Inter S/C Range Processing
SO 100 Terrestrial Probe, NER
Large Field Arrays
Parabolic S/C Envelope Models & Data Visualization
Computational Techniques

SST-2 Terrestrial Probe
SET Detector Technologies
Multi-Aspect Thermal Decontamination
Radiation Hardening
Spacecraft Receivers
Human Health Care System
X-Ray Spectra Technology
Remote Sensor Based Michelle Gas Analysis
High Resolution Spectrometer

SPAC SPACE TECHNOLOGY PROGRAM

Science Observatory Sensing Systems Science Information

DIRECT DETECTORS TELESCOPE SYSTEMS PROBES AND PENETRATORS ARCHIVING AND RETRIEVAL

WEST MILLIMETER LASER SENSO OPTICAL SYSTEMS SAMPLE ACQUISITION ANALYSIS AND PRESERVATION DATA VISUALIZATION AND ANALYSIS

ACTIVE MICROWAVE COOLERS & CRYOGENICS CRYPTOGRAPHY

PASSIVE MICROWAVE PRECISION INSTRUMENT POINTING

SENSOR READOUTS MICRO-PRECISION CSI

OPTOELECTRONICS

JUNE 17, 1991

ORIGINAL PAGE IS OF POOR QUALITY
SCIENCE SENSING TECHNOLOGY PROGRAM

BASE PHILOSOPHY

- MAINTAIN INNOVATIVE R & T TO ENABLE NEW CAPABILITIES IN FOCUSSED TECHNOLOGY AREAS.
- DEVELOP AND DEMONSTRATE OPTIONS FOR NEW SENSOR CONCEPTS.
- INDEPENDENT OF USER ENDORSEMENT (TECHNOLOGY PUSH).
- LONG-TERM INVESTMENT, WITH ULTIMATE PROGRAMMATIC BENEFIT.
- TASK TURNOVER TO FOCUSSED ELEMENTS WHEN SUCCESSFUL PROOF-OF-CONCEPT ACHIEVED.
SCIENCE SENSING TECHNOLOGY PROGRAM

SENSOR BASED PROGRAM

- SENSOR MATERIALS RESEARCH
- INNOVATIVE SENSOR DEVICE RESEARCH
- SENSOR SUPPORT TECHNOLOGY

SENSOR BASE PROGRAM

SENSOR MATERIALS
  - LASER MATERIALS
  - X - RAY AND GAMMA RAY MATERIALS
  - DIRECT DETECTOR MATERIALS

INNOVATIVE SENSOR DEVICE RESEARCH
  - X - RAY QUANTUM MICRO - CALORIMETER
  - COSMIC - RAY STRIP DETECTOR
  - X - RAY AND GAMMA - RAY DETECTORS
  - IR DETECTORS
  - DIRECT DETECTORS

SENSOR AND OPTICAL TECHNOLOGY
  - NO ACTIVITY

6/24/91
Comparison of Fe-55 spectrum taken with a calorimeter with superconducting Ta absorber (see insert) and a solid state detector (curve with markers). The resolution of the calorimeter is 30 eV FWHM, 5 times better than the solid state detector. Of this 30 eV, 20 eV is due to the superconducting absorber. Our goal is to reduce this contribution.

JPL

Silicon Micromachined Infrared Tunnel Sensor

- Uncooled broadband sensor (1 μm to 1000 μm)
- Order of magnitude improvement in the sensitivity over pyroelectric detector.
- Silicon micromachining used to fabricate all sensor components.
- Array compatibility, integration with electronics and low-cost batch fabrication are feasible.
SENSOR BASE PROGRAM
ACCOMPLISHMENTS

- SENSOR MATERIALS
  - MERCURY ZINC TELLURIDE IR MATERIALS.
  - MERCURY IODIDE SINGLE CRYSTALS FOR X - RAY / GAMMA RAY DETECTORS.
  - LASER DIODE MATERIALS.
  - SOLID - STATE LASER MATERIALS.
  - QUANTUM - WELL / SUPERLATTICE MATERIALS.

- INNOVATIVE SENSOR DEVICE RESEARCH
  - LASER INJECTION LOCKING OF ALEXANDRITE LASER.
  - X - RAY CALORIMETER WITH SUPERCONDUCTING ENERGY CONVERTER.
  - SOLID - STATE PHOTOMULTIPLIED.
  - IR DETECTOR ARRAY LOW - TEMPERATURE READOUT.
  - DIODE - PUMPED NEODYMIUM YAG LASER.

- SENSOR AND OPTICAL TECHNOLOGY
  - RAMAN FREQUENCY CONVERSION FOR MID - IR LASER.

SENSOR BASE PROGRAM
AUGMENTATION

- SENSOR MATERIALS RESEARCH
  - THIN FILMS SEMICONDUCTORS
  - OPTICAL MATERIALS
  - NANO TECHNOLOGY
  - SUPERCONDUCTIVITY

- INNOVATIVE SENSOR DEVICE RESEARCH
  - X - RAY, GAMMA RAY, UV, IR DETECTORS
  - HETERODYNE RECEIVERS
  - MICROSENSORS
  - SPACE ENVIRONMENTAL EFFECTS

- SENSOR AND OPTICAL TECHNOLOGY
  - ADVANCED OPTOELECTRONICS
  - OPTICS AND MICROWAVE TECHNOLOGY
  - ADVANCED METROLOGY AND CALIBRATION
## SCIENCE SENSOR TECHNOLOGY
### FOCUSED PROGRAM FUNDING

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### SENSOR BASE PROGRAM
#### (AUGMENTED)

- SENSOR MATERIALS RESEARCH
  - BANDGAP ENGINEERED MATERIALS FOR SENSORS, LASERS, MICROWAVE DEVICES.
  - NOVEL HETEROSTRUCTURE MATERIALS FOR MICROWAVE DEVICES.
  - NON-LINEAR OPTICAL MATERIALS.
  - GUIDED-WAVE MATERIALS AND PROCESSING TECHNIQUES.
  - NEW - SUBSTRATE MATERIALS AND PROCESSING TECHNIQUES.
  - NEW MATERIALS FOR SOLID-STATE LASERS.
  - ELECTRON BEAM LITHOGRAPHY OF SENSOR COMPONENTS.
  - SCANNING TUNNELING MICROSCOPY AND BALLISTIC ELECTRON EMISSION SPECTROSCOPY.
  - NANOMETER-SCALE LITHOGRAPHY FOR NOVEL ELECTRONIC DEVICES.
SENSOR BASE PROGRAM
(AUGMENTED)

- INNOVATIVE SENSOR DEVICE RESEARCH
  - NEW HIGH Z ABSORBERS FOR CALORIMETERS.
  - RADIATION HARD X-RAY CCD's.
  - RADIATION HARD SUB-ELECTRON READOUT CCD's.
  - HIGH BANDGAP CCD's AND OTHER ARRAYS.
  - SMART SENSORS FOR STAR TRACKING.
  - SUPERCONDUCTING BOLOMETERS.
  - PHOTON COUNTING TECHNOLOGIES.
  - HIGH OPERATING TEMPERATURE ARRAYS.
  - LOCAL OSCILLATOR WAVE SOURCES.
  - MILLIMETER-WAVE SUPERCONDUCTING PHASED ARRAYS.
  - PLANAR RECEIVER ARRAYS.

SENSOR BASE PROGRAM
(AUGMENTED)

- SENSOR AND OPTICAL TECHNOLOGY
  - ADVANCED LASERS, DETECTORS, AND ELECTRONICS FOR INTERCONNECTS.
  - INTEGRATED TECHNOLOGIES FOR MICROSENSOR APPLICATIONS.
  - FPA SIGNAL PROCESSING AND READOUT TECHNOLOGIES.
  - FOCAL-PLANE MICRO-OPTICS AND HOLOGRAPHIC OPTICAL ELEMENTS.
  - BINARY OPTICS.
  - PHASE CONJUGATE OPTICS.
  - LARGE APERTURE SCANNED ANTENNAS CONCEPTS.
  - SUBNANOMETER ACCURACY METROLOGY FOR LONG PATH LENGTH MEASUREMENTS.
  - GRAZING INCIDENCE OPTICS.
## SCIENCE SENSING TECHNOLOGY PROGRAM

### STATE OF THE ART

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<td>Sili x IBC (+12K)</td>
<td></td>
</tr>
<tr>
<td><strong>LWIR, ULWIR (5 - 30um)</strong></td>
<td>PV OR RSe Hg Cd Te 12um</td>
<td>LARGER PV ARRAYS 1 X 65K</td>
</tr>
<tr>
<td></td>
<td>Si IBC (+12K)</td>
<td>LARGER ARRAYS, LOW - NOISE READOUTS</td>
</tr>
<tr>
<td><strong>FIR (30 - 1 - 10um)</strong></td>
<td>STRESSED AND UNSTRESSED GeX</td>
<td>ARRAY CAPABILITY (SAME -4000 X 4000)</td>
</tr>
<tr>
<td></td>
<td>Si OR Ge BOLOMETERS (+1K)</td>
<td>LOW - NOISE READOUTS</td>
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<tr>
<td></td>
<td></td>
<td>VERY LOW NEP BELOW 10^-18 W/Hz</td>
</tr>
<tr>
<td><strong>BREADBOARD (1 - 1000um)</strong></td>
<td>PYROELECTRICS, THERMOPILES</td>
<td>HIGHER D* (&gt;100K)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LARGER ARRAYS (UP TO 1000 X 1000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LARGER ΔT</td>
</tr>
</tbody>
</table>

### SCIENCE SENSING

#### DIRECT DETECTORS

**TECHNOLOGY NEEDS:**

**EARTH SCIENCE (EOS)**
- OPERATING TEMPERATURE - 65K, -100K
- NEAR BACKGROUND - LIMITED (BLIP) SENSITIVITY
- LARGE ARRAYS

**PLANETARY (NEPTUNE / PLUTO, DISCOVERY PROGRAM**
- OPERATING TEMPERATURE (GREATER THAN -90K)
- THERMAL DETECTORS WITH HIGH D, HIGH BANDWIDTH, MODEST ARRAY FORMATS

**SPACE PHYSICS (SOLAR PROBE)**
- HIGH SENSITIVITY UV / X-RAY DETECTORS
- LARGE ARRAYS (UP TO -1000 X 1000)
- THERMAL DETECTORS WITH HIGH D, HIGH BANDWIDTH, MODEST ARRAY FORMATS

**ASTROPHYSICS (SIRTF, SMMM, LDR)**
- LARGE ARRAYS (SAME 2 - 4000 X 4000)
- LOW - BACKGROUND OPTIMIZATION - NEP BELOW 10^-18 W/Hz
- HIGHER - BACKGROUND OPTIMIZATION - BLIP, WITH FAST READOUTS
- CRYOGENIC, LOW - NOISE READOUTS

**BENEFITS:**

- LASER ARRAYS
- IMPROVED QUANTUM EFFICIENCY AND NOISE
- OPERATING TEMPERATURE CONSTRAINTS MINIMIZATION
- IMPROVED MATERIALS / PROCESSING
- DRAMATICALLY IMPROVED SCIENCE RETURN
MILESTONES - DIRECT DETECTORS

ONGOING
- Hg ZnTe MATERIALS - '93
- Ge BIB FOR FIR - '94
- READOUT TECHNOLOGY - '95
- II - VI MATERIALS - '95
- InAs nipi SUPERLATTICES FOR LWIR - '95
- MULTIPLE QUANTUM WELLS FOR LWIR - '96
- TUNNEL THERMAL DETECTOR - '96
- STRAINED LAYER SUPERLATTICE FOR LWIR - '97

AUGMENTED
- GAMMA AND X - RAY DETECTORS - '97
- BREADBOARD IR DETECTOR - '97
- UV - VISIBLE DETECTORS - '98
- LWIR DETECTORS - '98
- FAR - IR DETECTORS - '98
- SWIR DETECTORS - '99

ARC

Low-Background IR Detector Technology

- Develop and optimize low-background IR astronomy focal plane technologies
- Improve sensitivity, via lower noise and dark current
- Increase spectral coverage of arrays
- Achieve larger formats (to 512 x 512)

- Extremely low backgrounds, to <1 photon/s, require extremely low noise
- Low temperature operation (2 - 10 K)
- Long integration times (up to 10's of minutes)
- Long wavelengths (to 1000 μm)

- Excellent low-background characterization lab and staff at ARC
- Strong ties to SIRTF user community, and to DoD
- Next-generation readout electronics under development
- Leading Si array types being cross-compared for SIRTF

OAET

- Pioneered proton testing of IR arrays
- Conducted successful ground-based and airborne astronomical demos
- Achieved 50 electrons read noise in Si arrays
- Measured high responsivity in GaAs far-IR photon detector

SE1-12

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SCIENCE SENSING TECHNOLOGY PROGRAM

<table>
<thead>
<tr>
<th>STATE OF THE ART</th>
<th>TODAY</th>
<th>GOALS</th>
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<tr>
<td>SUBMILLIMETER WAVE DETECTORS</td>
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<tr>
<td>SMMM MIXERS</td>
<td>16 hv/k, 2000GHz</td>
<td>10hv/k, 400 - 1200 GHz</td>
</tr>
<tr>
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<td>40hv/k, 5000GHz</td>
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<tr>
<td>SMMM LOCAL OSCILLATORS</td>
<td>500w, 700 GHz, 300 µw, 492 GHz</td>
<td>50w, 400 - 1200 GHz</td>
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<tr>
<td>LDR MIXERS</td>
<td>SAME AS ABOVE</td>
<td>16 hv/k, 300 - 3000 GHz</td>
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<tr>
<td>LDR FOCAL PLANE ARRAY</td>
<td>NONE</td>
<td>2 x 10 ELEMENTS</td>
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<td>LDR LOCAL OSCILLATORS</td>
<td>SAME AS ABOVE</td>
<td>10 mw FOR ARRAYS</td>
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<tr>
<td>SPECTROMETER (GENERIC TO ALL)</td>
<td>500 GHz BW, 1MHz RESOLUTION</td>
<td>SMMM - 10,000 CHANNELS</td>
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<tr>
<td></td>
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<td>EOS - 20,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LDR - 20,000</td>
</tr>
</tbody>
</table>

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SE1-13
SCIENCE SENSING
SUBMILLIMETER SENSORS

TECHNOLOGY NEEDS:

HETERODYNE RECEIVER IS INSTRUMENT OF CHOICE FOR;
  - HIGH SPECTRAL RESOLUTION
  - HIGH SENSITIVITY

EARTH REMOTE SENSING APPLICATIONS - EOS MLS
  - DISCRETE FREQUENCIES: 640 GHz, 1800 GHz
  - OPTIMIZED FOR MODERATE BACKGROUND
  - SENSITIVITY AVAILABLE AT 640 GHz, BUT NOT AT 1800 GHz
  - RELIABILITY FOR 5 - 10 YEAR MISSION
  - PASSIVELY COOLED OPERATION (80 - 130K)

ASTROPHYSICS APPLICATIONS - SMIM, LDR, LUNAR INTERFEROMETER
  - CONTINUOUS FREQUENCY COVERAGE FROM 400 TO 1200 GHz
  - OPTIMIZED FOR BEST SENSITIVITY (LOW BACKGROUND)
  - LOCAL OSCILLATORS
  - CONDUCTING MIXERS AND FOCAL PLANE ARRAYS
  - RELIABILITY FOR 1 - 2 YEAR MISSION
  - CRYOGENIC OPERATION (4K)

BENEFITS:
  - PUSHING TECHNOLOGY TO FREQUENCIES
    - NEAR TERM EMPHASIS TO 1200 GHz
    - FAR TERM EMPHASIS TO 3000 GHz
  - IMPROVED SENSITIVITY AN ORDER OF MAGNITUDE
  - DEVELOPING A VIABLE ARRAY TECHNOLOGY
  - DEVELOPING SPACE QUALIFIABLE COMPONENTS
    RELIABLE, LOW POWER CONSUMPTION, COMPACT

MILESTONES - SUBMILLIMETER WAVE DETECTORS

ONGOING

ASTROPHYSICS
  • BASELINE MIXERS - '95
  • NOVEL LOCAL OSCILLATORS - '95
  • SPECTROMETERS - '95
  • FOCAL PLANE ARRAYS - '95
  • BASELINE LOCAL OSCILLATORS - '96

EARTH REMOTE SENSING
  • BASELINE MIXER - '94
  • ADVANCED MIXER & LO'S - '96

SPACE PHYSICS
  • ADVANCED IR RECEIVERS - '97

AUGMENTED
  • HETERODYNE - '96
  • ASTRO ARRAYS - '96
  • ASTRO MIXERS AND LO's - '97
  • EARTH SENSING - '97
  • SPECTROMETER - '98
SCIENCE SENSING
LASER SENSING

TECHNOLOGY NEEDS:

EARTH PLANETARY REMOTE SENSING APPLICATIONS (EOS)
- EYE - SAFE DOPPLER LASER (LAWS) / SPACE QUALIFIABLE
- EYE - SAFE DIAL (LASAR) / SPACE QUALIFIABLE
- RANGE / ALTIMETER LASERS (GLRS) (PLANETARY MOLAR)
- IN - SITU LASERS

BENEFITS:

TERRESTRIAL AND PLANETARY SCIENCE INSTRUMENTS TO MEASURE:
- WIND SPEED
- PRESSURE / TEMPERATURE
- GREENHOUSE GASES
- TRACE SPECIES: O₃, C/₂
- TECTONIC PLATE MOVEMENT
- ICE - PACK MOVEMENT

METROLOGY FOR SPACE VLBI
AIRBORNE UV DIAL SYSTEM SCHEMATIC

LASER WAVELENGTHS TRANSMITTED SIMULTANEOUSLY
IN NADIR AND ZENITH DIRECTIONS

$\lambda_{on} \quad 286\text{nm}$  DIAL $\text{O}_3$ PROFILES
$\lambda_{off} \quad 300\text{nm}$  
$\lambda_{off} \quad 600\text{nm}$  AEROSOL雲CLOU DOP
SPACE QUALIFICATION

- ISSUES -

• LIFETIME
• RELIABILITY / STABILITY
• GRACEFUL DEGRADATION

WALL PLUG EFFICIENCY

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MILESTONES - LASER SENSING

ONGOING
- STREAK TUBE RECEIVER - '93
- PROTOTYPE CO2 LASER TRANSMITTER FOR LAWS - '93
- PROTOTYPE 2 MICRON - LASER - '94
- Ti - SAPPHIRE PULSE LASERS - '95
- TUNABLE SOLID - STATE LASER MATERIALS - '95
- OPTICAL PARAMETRIC OSCILLATOR MATERIALS - '95
- SEMICONDUCTOR DIODE LASER PUMPS - '96
- RING LASER MASTER OSCILLATOR - '97

AUGMENTED
- HIGH - POWER LASER DIODE PUMP ARRAY - '95
- SOLID - STATE DOPPLER LIDR DEMO - '96
- BREADBOARD NEAR - IR SYSTEMS DEMO - '95
- BREADBOARD MID - IR SYSTEM DEMO - '97
- ENGINEERING MODEL OF >100 mJ 1KHz ALTIMETER - '98
### REQUIREMENTS for LASER SUBSYSTEM

<table>
<thead>
<tr>
<th>REQUIREMENT</th>
<th>CONCEPT WAVELENGTH</th>
<th>MOTIVATION</th>
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</thead>
<tbody>
<tr>
<td>ENERGY PER PULSE</td>
<td>10-20 J</td>
<td>SNR</td>
</tr>
<tr>
<td>PULSE LENGTH</td>
<td>3 μsec</td>
<td>RANGE/VEL. RESOLUTION</td>
</tr>
<tr>
<td>REPETITION RATE</td>
<td>10 pps</td>
<td>COVERAGE</td>
</tr>
<tr>
<td>CHIRP</td>
<td>&lt;200 kHz</td>
<td>VEL. RESOLUTION</td>
</tr>
<tr>
<td>BANDWIDTH</td>
<td>SINGLE FREQUENCY</td>
<td>VEL. RESOLUTION</td>
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<tr>
<td>BEAM QUALITY</td>
<td>NEAR D.L.</td>
<td>SYSTEM EFFICIENCY</td>
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<tr>
<td>EFFICIENCY (WALL PLUG)</td>
<td>5 %</td>
<td>PRIME POWER</td>
</tr>
<tr>
<td>LIFETIME</td>
<td>10 SHOTS</td>
<td>MISSION DURATION</td>
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<tr>
<td>MASS</td>
<td>&lt;150 kg</td>
<td>PLATFORM ACCOMMOD.</td>
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<tr>
<td>OTHER</td>
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<td>SPATIAL COHERENCE</td>
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## LASER CONCEPTS SUMMARY

<table>
<thead>
<tr>
<th>ITEM</th>
<th>CO₂</th>
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<tbody>
<tr>
<td>PULSE ENERGY &gt; 10 J</td>
<td>DEMONSTRATED</td>
</tr>
<tr>
<td>PRIME ENERGY</td>
<td>ALL SOLID STATE PULSE POWER IN EXISTENCE</td>
</tr>
<tr>
<td>PULSE REPETITION RATE (at REGD. ENERGY)</td>
<td>DEMONSTRATED</td>
</tr>
<tr>
<td>COHERENCE</td>
<td>DEMONSTRATED</td>
</tr>
<tr>
<td>WALL PLUG EFFICIENCY (&gt;5%)</td>
<td>6 - 8%</td>
</tr>
<tr>
<td>LIFETIME</td>
<td>10^8 COMMERCIALY</td>
</tr>
<tr>
<td>FREQUENCY STABILITY</td>
<td>DEMONSTRATED</td>
</tr>
<tr>
<td>EYE SAFETY</td>
<td>EYE SAFE</td>
</tr>
</tbody>
</table>

## SCIENCE SENSING COOLERS & CRYOGENICS

### TECHNOLOGY NEEDS:

- THE COOLERS AND CRYOGENICS TECHNOLOGY PROGRAM WILL SUPPORT THE FULL RANGE OF SPACE SCIENCE INSTRUMENT COOLING AND CRYOGENIC TECHNOLOGY NEEDS, INCLUDING:
  - EARTH OBSERVING SYSTEM INFRARED INSTRUMENTS REQUIRE LOW VIBRATION 30 TO 65 K COOLERS
  - EOS AND GEOPLATFORM INSTRUMENTS
  - HUBBLE SPACE TELESCOPE (HST) REPLACEMENT INSTRUMENT AND HST FOLLOW-ON REQUIRE 10 TO 80 K VIBRATION - FREE COOLERS
  - HST, LTT, NGST, ST - NO, IMAGING INTERFEROMETER
  - SUBMILLIMETER, LWIR AND X-RAY ASTROPHYSICS MISSION REQUIRE LONG - LIFE 2 - 5 K LOW - VIBRATION COOLERS
    - SMM, LDR, SMLs, SMM, AXAF

### BENEFITS:

- DEVELOP AND DEMONSTRATE A LONG LIFETIME 30K STIRLING CYCLE COOLER (GSFC)
- FOCUSED PROGRAM TO PROVIDE 30K COOLER FOR EOS - B INSTRUMENTS
- BRASSBOARD COOLER WILL DEMONSTRATE 5 YEAR LIFETIME, LOW VIBRATION (LESS THAN 0.05 POUND FORCE), 300 MW OF COOLING POWER AT 30K, HIGH EFFICIENCY (LESS THAN 75 WATT INPUT POWER) AND EASE OF INTEGRATION
- FLIGHT OF A 65K STIRLING COOLER (JPL)
  - DEMONSTRATE LOW VIBRATION OPERATION IN SPACE
  - DEMONSTRATE SOLUTIONS FOR COOLER TO INSTRUMENT INTERFACE ISSUES
- MAINTAIN LOW LEVEL FOR R & D ON ADVANCED COOLER CONCEPTS
  - DEVELOP COOLER TECHNOLOGY TO PROVIDE NEXT GENERATION COOLERS
  - DEVELOP SUB - KELVIN REFRIGERATION
MILESTONES - COOLERS AND CRYOGENICS

ONGOING
- LONG - LIFE 36K STIRLING CYCLE COOLER - '96
- FLIGHT OF 65K STIRLING COOLER - '96
- SUBKELVIN DILUTION REFRIGERATION - '97
- ADVANCED PASSIVE COOLER - '97
- MAGNETIC COOLER CONCEPTS - '01

AUGMENTED
- PULSE - TUBE AND ADVANCED PASSIVE COOLERS - '99
- 2 - 5K LONG LIFE MECHANICAL REFRIGERATION - '02
- LONG LIFE VIBRATION - FREE COOLER DEVELOPMENT - '05

STIRLING COOLER CHARACTERIZATION RESEARCH

OBJECTIVE: Develop the technology base required to utilize Stirling coolers in sensitive science instruments

APPROACH: Research the fundamental physics underlying cooler performance
- Vibration and EMI
- Lifetime and Reliability
- Thermal Performance

PROGRESS: Pathfinder experiments with JPL's BAe Stirling-cycle cooler have resulted in much improved understanding of the cooler's thermal and vibration performance

JPL TESTING HAS QUANTIFIED THE EXISTENCE OF STRONG COOLER VIBRATION AT FREQUENCIES UP TO 500 Hz

ADVANCED JPL INSTRUMENTATION HAS IDENTIFIED IMPROVED COOLER THERMAL PERFORMANCE

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SCIENCE SENSING TECHNOLOGY PROGRAM

**ACTIVE MICROWAVE SENSORS**

**TECHNOLOGY NEEDS:**

- THE ACTIVE MICROWAVE SENSORS TECHNOLOGY PROGRAM WILL SUPPORT THE FULL RANGE OF SPACE RADAR SCIENCE INSTRUMENT TECHNOLOGY NEEDS, INCLUDING:
  - EARTH OBSERVING SYSTEMS (EOS)
    - EOS SYNTHETIC APERTURE RADAR (L-, C-, X-BANDS, POLARIZATION)
    - EOS SCATTEROMETER (SCANSAT)
  - TOPOGRAPHICAL MISSIONS
    - TOPSAT RADAR ALTIMETER (Ka-BAND INTERFEROMETER)
  - METEOROLOGICAL RADAR MISSIONS
    - RAIN RADAR (X-, Ka-BAND, LEO)
    - GEOSTATIONARY RAIN RADAR (Ka, W BAND)
  - ADVANCED PLANETARY RADAR MAPPERS
    - LUNAR SOUNDERS (< P-BAND), MARS LANDER (Ka-BAND?)

**BENEFITS:**

- THIS EFFORT WILL LEAD TO THE DEVELOPMENT OF LIGHT, CONFORMAL ARRAY DESIGNS UTILIZING MMIC TRANSMIT / RECEIVE MODULES OPERATING BETWEEN 0.5 - 90 GHz AND ENHANCED FLEXIBILITY WITH ADVANCED DIGITAL CORRELATORS INCORPORATING HIGH THROUGHPUT, PRECISION AND IMPROVED FLEXIBILITY WITH ADVANCED POLARIMETRY AND SCANSAR ALGORITHMS.
MILESTONE ACTIVE MICROWAVE SENSING

ONGOING

AUGMENTED
- 1 - 10 GHz MMIC ARRAYS - '95
- ASIC DIGITAL SYSTEM - '96
- 35 GHz COMPONENTS AND ARRAYS DEVELOPMENT - '97
- CALIBRATION SUBSYSTEMS - '98
- 94 GHz COMPONENTS AND ARRAY DEVELOPMENT - '01

ADVANCED RADAR TECHNOLOGY
EOS SAR ANTENNA TECHNOLOGY

JPL

SIR-C T/R MODULE
SIR-C L-BAND PANEL
LARGE ARRAY DESIGNS
ARRAY DEPLOYMENT MECHANISMS

MMIC DEVELOPMENT
LIGHT WEIGHT PANEL DESIGN
LIGHT WEIGHT STRUCTURE
A/C PROTOTYPE
EOS SAR DEMO ON SIR-C FLIGHT

PROTOTYPE STRUCTURE

6/24/91

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## SCIENCE SENSING TECHNOLOGY PROGRAM

**OAET**

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<th>&gt; 10 YR. 2000</th>
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<tr>
<td>SENSOR ELECTRONICS</td>
<td></td>
<td>EOS SAR</td>
<td>RAIN RADAR GEO</td>
</tr>
<tr>
<td>Low - temperature operation</td>
<td>15 k using CMOS</td>
<td>2 - 4k</td>
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<tr>
<td>Low read noise</td>
<td>3 - 5 electron rms in CCD's 30</td>
<td>1 electron rms</td>
<td></td>
</tr>
<tr>
<td>Large array size</td>
<td>256 x 256 (IR), 2048 x 2048 (CCD)</td>
<td>$10^4 \times 10^4$</td>
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</tr>
<tr>
<td>High throughput</td>
<td>0.01 pixels / s</td>
<td>&gt; 100 FPS</td>
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</tr>
<tr>
<td>Low - power VHSIC</td>
<td>100 fJ</td>
<td>0.5 fJ</td>
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<tr>
<td>Array buttability</td>
<td>3 sides</td>
<td>4 sides</td>
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### SCIENCE SENSING SENSOR ELECTRONICS

**OAET**

**TECHNOLOGY NEEDS:**

- EARTH SCIENCE (EOS) AND ASTROPHYSICS (SIRTF, LDR)
  - CYROGENIC OPERATION (2 - 4K)
  - SUBELEMENT NOISE (1 ELECTRON - RMS)
  - HIGH THROUGHPUT (> 100 FPS)
  - LOW POWER CONSUMPTION (0.5 fJ)
  - LARGE ARRAY SIZE (10 X 10)

**BENEFITS:**

- INCREASED ELECTRONICS INTEGRATION
- LOW - NOISE CYROGENICS DEVICES FOR IR FPA READOUT
- LARGE FORMAT MOSAIC PACKAGING
- LESS COMPLEXITY

---

SE1-24
MILESTONES - SENSOR ELECTRONICS

ONGOING

AUGMENTED

- LOW POWER VHSIC - '96
- SUB ELECTRON READ NOISE - '97
- ADVANCED PACKAGING AND INTERFACES - '00
- CRYOGENIC READOUT ELECTRONICS - '01
- ADVANCED READOUT ARCHITECTURE - '02
SCIENCE SENSING TECHNOLOGY PROGRAM

PASSIVE MICROWAVE SENSING

<table>
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<tr>
<th>Technology Needs:</th>
<th>Benefits:</th>
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<tbody>
<tr>
<td>EARTH OBSERVING SYSTEM (EOS) PASSIVE MICROWAVE SENSORS</td>
<td>EXTENDED MEASUREMENT TO:</td>
</tr>
<tr>
<td>- ADVANCED EOS-B MULTIFREQUENCY IMAGING MICROWAVE RADIOMETER (MIMR)</td>
<td>- DEVELOP IN-SPACE CALIBRATION METHODOLOGY</td>
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<tr>
<td>- ADVANCED MICROWAVE LIMB SOUNDER</td>
<td>- IMPROVE RADIOMETER FRONT-END SENSITIVITIES</td>
</tr>
<tr>
<td>GEOSTATIONARY PLATFORM</td>
<td>IMPROVED ACCURACY OF MEASUREMENTS</td>
</tr>
<tr>
<td>- LOW FREQUENCY RADIOMETER (6 - 60 GHz)</td>
<td>- DEVELOP IN-SPACE CALIBRATION METHODOLOGY</td>
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<tr>
<td>- HIGH FREQUENCY RADIOMETER (60 - 220 GHz)</td>
<td>- IMPROVED RADIOMETER FRONT-END SENSITIVITIES</td>
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<tr>
<td>SUBMILLIMETER MODERATE MISSION</td>
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</tr>
<tr>
<td>- ACOUSTO-OPTICAL OR DIGITAL SPECTROMETER</td>
<td></td>
</tr>
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</table>

TECHNOLOGY NEEDS:

- EARTH OBSERVING SYSTEM (EOS) PASSIVE MICROWAVE SENSORS
  - ADVANCED EOS-B MULTIFREQUENCY IMAGING MICROWAVE RADIOMETER (MIMR)
  - ADVANCED MICROWAVE LIMB SOUNDER
- GEOSTATIONARY PLATFORM
  - LOW FREQUENCY RADIOMETER (6 - 60 GHz)
  - HIGH FREQUENCY RADIOMETER (60 - 220 GHz)
- SUBMILLIMETER MODERATE MISSION
  - ACOUSTO-OPTICAL OR DIGITAL SPECTROMETER

BENEFITS:

- EXTENDED MEASUREMENT TO:
  - DEVELOP IN-SPACE CALIBRATION METHODOLOGY
  - IMPROVE RADIOMETER FRONT-END SENSITIVITIES
- IMPROVED ACCURACY OF MEASUREMENTS
  - DEVELOP IN-SPACE CALIBRATION METHODOLOGY
  - IMPROVED RADIOMETER FRONT-END SENSITIVITIES
MILESTONES - PASSIVE MICROWAVE SENSING

ONGOING

AUGMENTED

- LARGE APERTURE RADIOMETER (HIGH FREQUENCY) - '97
- SYNTHETIC APERTURE RADAR (LEO) - '99
- SYNTHETIC APERTURE RADAR (GEO) - '99
- LARGE APERTURE RADIOMETER (LOW FREQUENCY) - '02
- SENSOR MATERIALS AND PROCESSING - '05
- INNOVATIVE AND PROCESSING - '05
- SENSOR SUPPORT TECHNOLOGY - '05

SCIENCE SENSING TECHNOLOGY PROGRAM

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<th>&gt; 10 YR. 2000</th>
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<tr>
<td>SENSOR OPTICAL SYSTEM</td>
<td>Inadequate</td>
<td>EOS SAR</td>
<td>TOPOGRAPH RACKOR (GEO)</td>
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<tr>
<td>Modelling / analysis</td>
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<td>stray light, defraction, analysis</td>
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<tr>
<td>Metrology et nanometer laser</td>
<td>&gt; nanometer level</td>
<td>nanometer level and below</td>
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</tr>
<tr>
<td>Sensor optics components</td>
<td>inadequate</td>
<td>advanced gratings, filters, binary and</td>
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</tr>
<tr>
<td>Calibration</td>
<td>changes</td>
<td>holographic, phase conjugate optics, fiber optics</td>
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<td></td>
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<td>long-term stability in flight</td>
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SCIENCE SENSING
SENSOR OPTICAL SYSTEMS

TECHNOLOGY NEEDS:

- THE OPTICAL SENSOR RESEARCH PROGRAM WILL SUPPORT NEEDS OF THE FULL RANGE OF SPACE SCIENCE OPTICAL SENSOR NEEDS IN ALL PARTS OF THE SPECTRUM FROM HARD X-RAY TO 1 MM

ASTROPHYSICS
- AXAF, SIRTF, FUSE, SOFIA, AIM......

EARTH SCIENCE
- EOS

PLANETARY SCIENCE
- TOPS

SOLAR PHYSICS
- OSL

BENEFITS:

TECHNOLOGY ENABLES:

- FULL ACCESS TO THE ELECTROMAGNETIC SPECTRUM
- ORDER(s) OF MAGNITUDE IMPROVEMENT IN SENSITIVITY, SPATIAL AND SPECTRAL RESOLUTION, DYNAMIC RANGE
- LONG-TERM RADIOMETER STABILITY

TECHNOLOGY DEVELOPMENT APPROACH UTILITIES:

- BASE PROGRAM FOR LONG-TERM SUSTAINED, ADVANCED DEVELOPMENT
- ADVANCES STATE-OF-THE-ART IN OPTICAL MODELING, FABRICATION, MATERIALS CHARACTERIZATION, ASSEMBLY AND TEST

MILESTONES - SENSOR OPTICAL SYSTEMS

ONGOING

AUGMENTED

- INTERFEROMETER BEAM COMBINERS - '98
- STRAY LIGHT - '03
- TUNABLE FILTERS - '04
- INNOVATIVE OPTICS - '04
- INSTRUMENT METROLOGY - '04
- GRATING - '05
- OPTICAL COMPONENTS - '05
SCIENCE SENSING TECHNOLOGY
OTHER EFFORTS/ACTIVITIES

- NASA/OSSA
- NASA/SBIR
- DoD
- DARPA
- SDIO
- ESA
- NOAA
- NSF
- UNIVERSITIES
- INDUSTRY

SCIENCE SENSING TECHNOLOGY
INTERACTIVE ACTIVITIES

- NASA SENSOR WORKING SPACE GROUP
  NASA, OAET, OSSA, DOD, DOE, NIST

- ADVISORY GROUP ON ELECTRON DEVICES
  NASA, DOD

- AF/NASA SPACE TECHNOLOGY INDEPENDENT GROUP
  NAS, DOD (AF)

- INTELLIGENCE COUNCIL
  NASA, CIA
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<th>FY '92</th>
<th>FY '93</th>
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* STRATEGIC PROGRAM
INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

DIRECT DETECTOR PROJECT SUMMARY

SCIENCE SENSING PROGRAM AREA
OF THE
SPACE SCIENCE TECHNOLOGY PROGRAM

June 26, 1991

Office Of Aeronautics, Exploration And Technology
National Aeronautics And Space Administration
Washington, D.C. 20546

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

TECHNOLOGY NEEDS

BEING AT THE "HEART OF THE SYSTEM", THE PERFORMANCE OF DIRECT DETECTORS IS CRITICAL TO NASA SCIENCE MISSIONS (Earth Science, Astrophysics, Planetary, Space Physics). KEY TECHNOLOGY NEEDS INCLUDE:

• GAMMA- AND X-RAY
  Position sensitivity (i.e., arrays)
  Improved energy resolution
  Low-noise preamplifiers

• UV & VISIBLE
  Improved quantum efficiency
  Extended spectral coverage
  Custom CCD production capability

• INFRARED
  Larger arrays
  Higher operating temperature (e.g., > 65 K)
  Improved quantum efficiency
  Lower noise
  Improved broadband detectors
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

TECHNOLOGY CHALLENGES/APPROACH

• TECHNOLOGY DEVELOPMENT CHALLENGES

- PRODUCE LARGER ARRAYS, WITH SMALLER PIXELS
- INCREASE OPERATING TEMPERATURE; PRESERVE/IMPROVE SENSITIVITY
- ACHIEVE LONG-TERM STABILITY
- IMPROVE RADIATION HARDNESS OF DETECTOR ARRAYS

• TECHNOLOGY DEVELOPMENT APPROACHES

- PURSUE PARALLEL DEVELOPMENT THRUSTS
  - REFINING AND OPTIMIZE PRESENTLY-EMERGING TECHNOLOGIES (e.g., HgGe for high-energy; InSb for SWIR; CCDs for UV/VIS/HIR)
  - DEVELOP INNOVATIVE CONCEPTS (e.g., new bandgap-engineered detectors, solid state drift chamber)

- IMPROVE MATERIAL PROPERTIES (e.g., purity, size, lifetime, crystallinity, surface passivation)

- EXPLOIT LATEST FABRICATION TECHNIQUES (MBE, MOCVD, LPE)

- THOROUGHLY CHARACTERIZE, AND CONDUCT EARLY DEMOS OF, PROTOTYPES

STATE-OF-THE-ART ASSESSMENT

<table>
<thead>
<tr>
<th>Spectral Band</th>
<th>Existing Technology</th>
<th>Status/Limitations</th>
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</thead>
<tbody>
<tr>
<td>Gamma- and X-ray</td>
<td>Discrete detectors</td>
<td>No imaging capability</td>
</tr>
<tr>
<td></td>
<td>- High-purity Ge and Si</td>
<td>Low quantum efficiency</td>
</tr>
<tr>
<td></td>
<td>- Mercuic iodide (Hgl₂)</td>
<td>Limited energy resolution</td>
</tr>
<tr>
<td></td>
<td>- Proportional counters</td>
<td>Small detector size</td>
</tr>
<tr>
<td></td>
<td>Scintillator-microchannel plates</td>
<td></td>
</tr>
<tr>
<td>UV and visible</td>
<td>SI CCDs (≤2048 x 2048)</td>
<td>Limited QE</td>
</tr>
<tr>
<td></td>
<td>Microchannel plates (≥1024 x 1024)</td>
<td>Limited spectral coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No solar rejection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radiation susceptibility</td>
</tr>
<tr>
<td>SWIR (1-5 μm)</td>
<td>HgCdTe and InSb arrays (256x256)</td>
<td>Limited array size</td>
</tr>
<tr>
<td></td>
<td>PtSi Schottky diode arrays (512x512)</td>
<td>Low quantum efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low temperature required</td>
</tr>
<tr>
<td>LWIR (5-30 μm)</td>
<td>HgCdTe to -15 μm</td>
<td>Limited spectral response</td>
</tr>
<tr>
<td></td>
<td>SI:As IBC arrays (128 x 128) for T&lt;12 K</td>
<td>Low temperature required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low yield</td>
</tr>
<tr>
<td>Far IR (30-1000 μm)</td>
<td>Discrete bolometer arrays</td>
<td>No integrated arrays</td>
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<tr>
<td></td>
<td>Bulk Ge:x photoconductors</td>
<td>Poor QE</td>
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<td>No mux'ing for bolometers</td>
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<tr>
<td></td>
<td></td>
<td>Radiation susceptibility</td>
</tr>
<tr>
<td>Broadband (1-1000 μm)</td>
<td>Pyroelectrics</td>
<td>Poor QE</td>
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<tr>
<td></td>
<td>Thermopiles</td>
<td>Poor frequency response</td>
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<tr>
<td></td>
<td></td>
<td>Small discrete arrays</td>
</tr>
</tbody>
</table>
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

CURRENT PROGRAM

- DEVELOP INFRARED ARRAY TECHNOLOGY FOR SPACE ASTROPHYSICS (ARC)
  - 256 x 256 InSb arrays
  - 10 x 50 Si:x impurity band conduction arrays; discrete SSPMs
  - Ge:x (incl. Ge:x IBC) and GaAs far-IR detectors
  - Low-T readouts (Si MOSFETs for <10 K)

- DEVELOP HIGH-ENERGY DETECTOR CONCEPTS FOR ASTROPHYSICS AND SPACE PHYSICS (GSFC)
  - Microcalorimeter/Far-IR bolometer (0.1 kelvin)
  - Cosmic ray strip detectors
  - Hgl2 detectors

- DEVELOP ADVANCED DETECTORS FOR PLANETARY, EARTH SCIENCE, AND ASTROPHYSICS MISSIONS (JPL)
  - Multiple quantum well arrays (e.g., GaAs/AlGaAs) for MWIR/LWIR
  - Superlattices: Strained-layer; InAs nlpl for LWIR
  - Heterojunction Internal Photoemission (HIP) detectors
  - Ge:Ga IBC detectors

- DEVELOP ALTERNATIVES TO HgCdTe FOR INFRARED EARTH SCIENCE SENSING (LaRC)
  - HgZnTe PC array (18 μm cutoff at 65 K) (270 x 1 elements)
  - II-VI Materials and Device Analysis

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

AUGMENTED PROGRAM

- INITIATE BROADLY-BASED PROGRAM IN GAMMA- AND X-RAY DETECTOR TECHNOLOGY, INCLUDING
  - Position-sensitive arrays (high-purity Ge, advanced x-ray CCDs, gas/liquid/solid interaction chambers)
  - Advanced cryogenic calorimeters
  - High-Z scintillator and APD system

- GREATLY EXPAND AND STRENGTHEN PROGRAM TO ADDRESS CHALLENGING PROBLEMS IN LWIR AND FAR IR
  - Optimized PV material development; bandgap engineered devices for higher T's
  - Novel photon counting devices
  - Larger array formats; novel dopants for IBC
  - MBE and MOCVD engineered multispectral band arrays

- INITIATE RESEARCH TO ADVANCE STATE-OF-THE-ART IN BROADBAND IR DETECTORS, INCLUDING
  - Advanced pyroelectric concepts for T = ~100 K
  - Optimized tunneling Golay cell concepts
  - High-T superconducting bolometers

- SUPPORT ADVANCEMENTS OF TECHNOLOGY BASE IN UV AND VISIBLE, INCLUDING
  - Advanced CCDs (incl. "solar blind", larger, & enhanced spectral response) or alternatives
  - Microchannel plates/micromachined Si
FOCUSED TECHNOLOGY PERFORMANCE OBJECTIVES

Example 1: High-Energy Detector (Imaging X-ray Spectrometer)

<table>
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<tr>
<th>MISSION REQUIREMENT</th>
<th>CURRENT SOA</th>
<th>REQUIRED CAPABILITY</th>
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<tbody>
<tr>
<td>Energy Resol (FWHM) (eV)</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td>Useable Range (keV)</td>
<td>0.4 - 4</td>
<td>0.25 - 10</td>
</tr>
<tr>
<td>Dimensions (mm²)</td>
<td>75 x 75</td>
<td>30 x 30</td>
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<tr>
<td>Readout Noise (e⁻⁻⁻)</td>
<td>1.5</td>
<td>&lt;0.5</td>
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<tr>
<td>Effective Pixel Size (µm)</td>
<td>30 x 30</td>
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<tr>
<td>Radiation Resistance</td>
<td>Low</td>
<td>&gt;15 kradls</td>
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Example 2: UV-Visible Detector (Si CCD Array for NGST)

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<tr>
<td>Array Size</td>
<td>800 x 800 (WF/PC 1)</td>
<td>15,000 x 15,000</td>
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<td>QE (0.1 - 0.4 µm) (%)</td>
<td>&gt;15</td>
<td>&gt;80</td>
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<tr>
<td>QE (0.4 - 1 µm) (%)</td>
<td>&gt;15</td>
<td>&gt;80</td>
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<tr>
<td>Well Capacity (e⁻⁻⁻⁻)</td>
<td>3 x 10⁴</td>
<td>1 x 10⁵</td>
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<tr>
<td>Pixel Size (µm)</td>
<td>15</td>
<td>5</td>
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<tr>
<td>Visible Blindness</td>
<td>&lt;10⁻⁴</td>
<td>&lt;10⁻⁹</td>
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<td>Read Noise (e⁻⁻⁻⁻⁻)</td>
<td>10</td>
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<td>Operating Temp (°C)</td>
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<tr>
<td>Mosaic Capability</td>
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<td>Buttable for 2-d mosaic</td>
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### FOCUSSED TECHNOLOGY PERFORMANCE OBJECTIVES

#### Example 3: Infrared Detector (Ge:Ga IBC Array)

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<td>Detector Type</td>
<td>Ge:Ga bulk photoconductor</td>
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<td>Spectral Range (μm)</td>
<td>60 - 120</td>
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<td>Array Format</td>
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<td>Array Type</td>
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<td>Operating Temperature (K)</td>
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<td>Readout Temperature (K)</td>
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<td>Noise Equivalent Power (W/√Hz; 1 s integration)</td>
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<td>Quantum Efficiency (%)</td>
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<td>≥40</td>
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<td>Radiation Susceptibility</td>
<td>High</td>
<td>Low</td>
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### TECHNOLOGY ROADMAP/SCHEDULE

#### Three Examples

- **User Community Participation & Oversight**
  - Large-volume, high-sensitivity Ge spectrometer
  - UV-optimized "solar-blind" CCD array
  - New LWIR options for >65 K operation

- **Focused R&T**
  - Gamma- and x-ray
  - UV-visible
  - SWIR
  - LWIR
  - Far IR
  - Broadband IR

- **Program Offices**
  - SE
  - SL
  - SS
  - SZ

- **R&T Base**
  - Advanced Detector Research

- **Options / Innovations**
  - Continuing Research

- **Continuing Research**

---

SE2-5
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

OTHER DEVELOPMENT EFFORTS

- **GAMMA- AND X-RAY**
  - Microcalorimeters (0.1 K) and CCDs (500 x 500) for AXAF
  - Concept study -- stacked Si(Li) detectors
  - Position sensitive HPGe study

- **UV and VISIBLE**
  - Si CCDs for HST II/STIS (2048 x 2048)
  - High-gain microchannel plates (12 μm channels)

- **SWIR**
  - 256 x 256 InSb for SIRTF (-10 K)
  - 256 x 256 HgCdTe for HST II/NICMOS (λ_c = 2.5 μm)

- **LWIR**
  - 128 x 128 Si:As IBC arrays for SIRTF (low-background)

- **FAR IR**
  - Stressed Ge:Ga arrays (to 4 x 16) for SIRTF
  - Semiconducting and superconducting bolometer concepts

- **BROADBAND IR**
  - Concept studies -- tunneling Golay cells and pyroelectrics
    - and a handful of SBIR Phase 1 and Phase 2 projects

*DoD work partially applicable

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

OTHER (Non-NASA) DEVELOPMENT EFFORTS

- **GAMMA- AND X-RAY**
  - DOE support of High-purity Ge and Hgl_2 for large-volume detectors

- **UV and VISIBLE**
  - Modest NSF support for optical CCD arrays for ground-based astronomy

- **SWIR**
  - DoD supports HgCdTe; PtSi Schottky; InSb development
  - Primarily for higher-backgrounds and rapid scan rates

- **LWIR**
  - DoD supports HgCdTe; AIGaAs/GaAs multiquantum well; InAsSb strained layer superlattice; Si:As IBC; many others
  - Primarily for higher-backgrounds and rapid scan rates

- **FAR IR**
  - None

- **BROADBAND IR**
  - Very limited DoD work on pyroelectrics and thermal detectors
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

PRELIMINARY FY 93 AUGMENTATION PRIORIZATION:

Focused Program

- LWIR and Far IR
- Gamma- and X-ray
- Broadband IR
- UV-Visible

FLIGHT EXPERIMENTS

(None)
## SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

### DIRECT DETECTORS

#### OUT-YEAR FUNDING (Ongoing/Augmentation) ($M)

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<td>1.5</td>
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<td>B. UV and visible</td>
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<td>0.1</td>
<td>0.2</td>
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<td>C. SWIR</td>
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<td>1.6</td>
<td>15.4</td>
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INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

SUBMILLIMETER SENSORS
PROJECT SUMMARY

SCIENCE SENSING PROGRAM AREA
OF THE
SPACE SCIENCE TECHNOLOGY PROGRAM

JUNE 26, 1991

Office of Aeronautics, Exploration and Technology
National Aeronautics and Space Administration
Washington, D.C., 20546

AGENDA

• SCIENCE BACKGROUND
• TECHNOLOGY CHALLENGES
• SUBMM-WAVE HETERODYNE RECEIVER
• STATE OF THE ART
• TECHNOLOGY BACKGROUND
• TECHNOLOGY PROGRAM
• NON-NASA SUPPORT
• FUNDING PROFILE
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

SUBMILLIMETER SCIENCE OBJECTIVES

- ASTROPHYSICS
  Addresses fundamental questions of astrophysics
  - Birth and death of stars
  - Galactic evolution
  Required data:
  - Composition (H2O,O2,O,C), mass, density, temperature, and velocity of material in interstellar medium

- EARTH REMOTE SENSING
  Characterize chemistry of ozone depletion in stratosphere
  Required data:
  - Species abundance, time dependence
  - Continuous day and night observation

TECHNOLOGY NEEDS

MISSION SET

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<th>Physics</th>
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<td>- LDR</td>
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<td>- EOS MLS 2nd Generation</td>
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<td>2000</td>
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Submillimeter Wavelength: 1000 to 100 μm or 300 to 3000 GHz

- Complete submillimeter wave, high resolution, spectral line survey of 100 astrophysical objects
  - 40 molecular clouds in the Milky Way
  - 30 galaxies
  - 30 sources of opportunity
- Sensitivity: Spectral line confusion limit ~2 mK
- Liquid Helium cooled focal plane
- SIS heterodyne receivers from 400 to 1200 GHz
- Scanning Fabry-Perot spectrometer from to 3000 GHz
- High elliptical orbit
- One to two year lifetime
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TYPICAL SPECTRUM FROM SMIM

Figure 1.3. A compressed view of the OVRO spectral line survey of OMC-1.
**Objective:**
100 sources

**Sensitivity:**
0.02 K noise

**Receiver figure of merit:** $T_{sys}$

**Need:**
$T_{sys} < 20 \text{ mK}$

---

**Eos MICROWAVE LIMB SOUNDER (MLS)**

- Study/monitor global change in stratosphere and mesosphere
  - Critical global monitoring of ozone chemistry
  - Monitoring of heterogeneous chemistry perturbations
- Sensitivity requirement: 0.1 K
- High spectral resolution receivers
  - 440 GHz, 560 GHz, 640 GHz, (1800 GHz)
  - GaAs Schottky subharmonically pumped mixers
- Radiative cooling of focal plane to 80 K
- 5 to 10 year lifetime
SUBMILLIMETER SENSORS

TYPICAL SPECTRUM FOR Eos-MLS
ASTROTECH 21 ADVISORY GROUP RECOMMENDATIONS

• Identified Four Technology Areas
  - Local oscillator development (frequency agile, broad band)
  - Mixer development (high sensitivity $T_{sys}=10 \, \text{hv/k}$, broad band, high IF)
  - Focal plane array development
  - Spectrometer development

• Identified Approach
  - Baseline development
    * Nb and NbN superconducting mixers
    * Multipliers driven by mm-wave source for local oscillator
  - Alternatives

• Participation by Submillimeter Wave Astrophysics Community
  - NASA centers
  - Universities

EOS MLS PRINCIPAL INVESTIGATOR RECOMMENDATIONS

• 600 GHz Class Receiver
  - Planar devices to replace whisker contacted devices
    * For both mixer and local oscillator device
  - Mixer development (moderate sensitivity, subharmonic, high IF)
  - Local oscillator development (moderate power)

• 1800 GHz Class Receiver
  - Local oscillator?
  - Circuit topology: Quasi-optical, planar, miniature waveguide?
Astrophysics Applications - SMIM, LDR, Lunar Interferometer
- Continuous frequency coverage from 400 to 1200 GHz, to 3000 GHz
- Optimized for best sensitivity (low background)
- Technology currently not available
  - Local Oscillators
    - Superconducting mixers and focal plane arrays
- Reliability for 1-2 year mission
- Cryogenic operation (4 K)

Earth Remote Sensing Applications - Eos MLS
- Discrete frequencies; 640 GHz, 1800 GHz
- Optimized for moderate background
- Sensitivity available at 640 GHz, but not at 1800 GHz
- Reliability for 5-10 year mission
  - Planar Schottky diodes
- Passively cooled operation (80-130 K)

Heterodyne Receiver is Instrument of Choice for
- High spectral resolution
- High sensitivity
Mixer combines submillimeter wave radiation (from molecules) with local oscillator radiation to reproduce the sources spectrum in the microwave band.

Key components are the mixer and the local oscillator.

Current OAET program has developed Nb and NbN SIS tunnel junctions with highest sensitivity and frequency performance reported to date.
Current OAET program has:

a) Developed high performance multipliers
b) Pioneered submm wave fundamental oscillator development using quantum well oscillators

MIXER ISSUES

- Efficient frequency conversion
  - Device: Sharp nonlinearity
  - Circuit: Optimum embedding impedance
- High sensitivity, low noise
  - Device: Low leakage current - shot noise
  - Low operating temperature - thermal noise
- High frequency operation
  - Device: High speed materials systems, small $\omega RC$ product
  - Circuit: Innovative transmission lines, tuning elements
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

MIXER DEVICES

Planar Schottky Diode

Superconductor Insulator
Superconductor (SIS) Tunnel Junction

Planar Schottky Diode

Superconductor Insulator
Superconductor (SIS) Tunnel Junction
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

Mixer Circuits

Waveguide Mixer
Machined Dimensions < $\lambda$

Planar Mixer Array
Machined Dimensions > $\lambda$

Original page is of poor quality
SIS MIXER MOUNTS

WAVEGUIDE MOUNT
- MATURE MIXER MOUNT
- OPERATIONAL TO 700 GHz
- NOT AMENABLE TO ARRAYS

PLANE MOUNT
- OPERATIONAL TO > 1500 GHz
- SINGLE MIXER AND ARRAYS
- NEW AND INNOVATIVE APPROACH

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

LOCAL OSCILLATOR ISSUES

Solid State Approaches

- Fundamental Oscillator
  - Efficient
  - High frequency operation very difficult

- Frequency Multiplication
  - Efficiency
    - Device: strong nonlinearity (C-V)
    - Circuit: optimum embedding impedance input, output and idler frequencies
  - High frequency operation
    - Device: small \( \omega \)RC, high speed materials system
    - Circuit: innovative transmission lines, tuning elements
GaAs Schottky Varactor

Planar bbBNN Varactor

Local Oscillator Devices

Local Oscillator Circuits

Crossed Waveguide Mount
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TECHNOLOGY PROGRAM OBJECTIVES

- Develop Key Components of Submillimeter Wave Heterodyne Receivers for Use in Space

- Performance Goals Include:
  - Pushing technology to higher frequencies
    - Near term emphasis to 1200 GHz
    - Far term emphasis to 3000 GHz
  - Improving Sensitivity an Order of Magnitude
  - Developing a Viable Array Technology
  - Developing Space Qualifiable Components
    Reliable, low power consumption, compact

- Program focussed on technology needs for the SMIM and LDR astrophysics missions and the EOS-MLS earth remote sensing mission
### TECHNOLOGY PROGRAM OBJECTIVES (details)

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<thead>
<tr>
<th>Mission Requirement</th>
<th>Current SOA</th>
<th>Objective</th>
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<tbody>
<tr>
<td><strong>SMIM LOs</strong></td>
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<tr>
<td>Output Power</td>
<td>50μW @ 700 GHz</td>
<td>50μW @ 400-1200 GHz</td>
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<td>Bandwidth</td>
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<tr>
<td>Sensitivity</td>
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<td>Bandwidth</td>
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<td><strong>LDR Mixers</strong></td>
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### TECHNOLOGY PROGRAM OBJECTIVES (details)

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<td>1800 GHz LO</td>
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...
SUBMILLIMETER SENSORS

CURRENT PROGRAM

- Astrophysics Baseline Technology
  - Initial demonstrations at 200, 600, 800 GHz

- Astrophysics Alternative technology
  - none

- Earth Remote Sensing Planar Diode Development
  - Initial demonstrations at 200 and 600 GHz

AUGMENTED PROGRAM

- Astrophysics Baseline Technology
  - Initial demonstrations above 1000 GHz
  - Optimization in 400-800 GHz range
  - Spectrometers

- Astrophysics Alternative Technology
  - Mixers
  - Local Oscillators
  - Focal Plane Mixer Arrays

- Greater Involvement from Universities

- Earth Remote Sensing Technology
  - 1800 GHz components
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TECHNOLOGY PROGRAM ELEMENTS

- Astrophysics Application [$6000K/year]
  - Baseline mixers
  - Baseline local oscillators
  - Backup/alternative mixer approaches
  - Backup/alternative local oscillator approaches
  - Spectrometers
  - Focal Plane Array

- Earth Remote Sensing [$1000K/year]
  - Baseline mixer - 640 GHz
  - Advanced mixers and LO’s - 1800 GHz

TECHNOLOGY PROGRAM ELEMENTS (details)

- Astrophysics Baseline Mixers
  - Nb, NbN SIS junctions feasibility for 800-1200 GHz
  - Nb, NbN SIS junction optimization for 600-800 GHz
  - Open structure mixer circuits feasibility, 800-1200 GHz
  - Waveguide mixer circuit optimization, 600-800 GHz

- Astrophysics Baseline Local Oscillators
  - Varactor diode feasibility for 800-1200 GHz
  - Planar GaAs Schottky diodes for 1st stage multipliers
  - Triplers and quintuplers for 800-1200 GHz
  - Waveguide multipliers for 1st stage multipliers

- Astrophysics Backup/Alternative Mixer Approaches
  - SIN mixers
  - Planar GaAs Schottky mixers for 800-1200 GHz
  - Micro-machined waveguide mounts for 800-1200 GHz

- Astrophysics Backup/Alternative Local Oscillator Approaches
  - Extended millimeter wave sources
  - Quantum Well Oscillators
  - Power Combining Arrays
  - Micro-machined Multiplier Circuits
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TECHNOLOGY PROGRAM ELEMENTS (details)

- Astrophysics Baseline Spectrometers
  - Broadband multichannel AOS Development
    (10,000 channels for SMMM)
    (200,000 channels for LDR)

- Astrophysics Focal Plane Arrays
  - Dielectrically Filled Parabola
  - Thin membranes with micromachined feeds

- Earth Remote Sensing Baseline Mixer
  - Planar GaAs Subharmonic mixer for 640 GHz
  - Planar devices for multipliers

- Earth Remote Sensing Advanced Mixers
  - 1800 GHz components

OTHER NON-NASA DEVELOPMENT EFFORTS

This effort is unique to NASA needs

NASA programs

- OAET Science Sensing Submillimeter Program
  - Goal: Focused technology development for mission set

- OSSA Astrophysics Research and Applications Program
  - Goal: Instrument Development (mm- and submmwave)

- OSSA Earth Sciences EOS MLS Development
  - Goal: Instrument Development (640 GHz)

- Internal JPL support
  - Goal: Focused technology development for mission set

- OAET University Centers of Excellence - Space Terahertz Technology Center at the University of Michigan
  - Goal: Generic technology development

SDIO program (small)

- Superconducting Technology
  - Goal: Superconducting focal plane receiver
### FUNDING PROFILE

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Significant Augmentation required to:
- Demonstrate technology above 800 GHz
- Optimize technology in 400 - 800 GHz range
- Pursue alternative technology

Timely Augmentation required to meet mission schedule needs

### TECHNOLOGY ROADMAP / SCHEDULE

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</table>

- 640 GHz Planar
- 1800 GHz
- Continuing
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

LASER SENSORS

Norman P. Barnes
June 27, 1991

Office of Aeronautics, Exploration, and Technology
National Aeronautics and Space Administration

TECHNOLOGY NEEDS

DEVELOP LASER REMOTE SENSORS TO MONITOR ESSENTIAL ATMOSPHERIC VARIABLES

• PLANET EARTH
  - DOPPLER LIDAR FOR WIND SPEED
  - LIDAR FOR AEROSOL CONCENTRATION
  - DIAL FOR GAS-CONCENTRATION
    WATER VAPOR
    OXYGEN FOR PRESSURE/TEMPERATURE
    GREENHOUSE GASES
    OZONE

• PLANETARY EXPLORATION, MARS
  - LIDAR FOR DUST
  - ATMOSPHERIC DENSITY FOR AEROBRAKING
TECHNOLOGY CHALLENGES AND APPROACH

• TECHNOLOGY CHALLENGES
  - HIGH EFFICIENCY
  - $5 \times 10^9$ SHOT LIFETIME
  - PROVIDE CONTINUOUS TUNING
    NEAR-INFRARED
    MID-INFRARED

• TECHNOLOGY APPROACH
  - EFFICIENCY
    LASER DIODE PUMPING
    MATERIAL SELECTION
    OPERATING TEMPERATURE
  - LIFETIME
    LASER DIODE PUMP
    RELIABLE OPTICS
  - TUNING
    TUNABLE LASER, NEAR-IR
    NONLINEAR OPTICS, MID-IR

STATE OF THE ART ASSESSMENT

• HIGH EFFICIENCY
  - 0.07 Nd:YAG, LASER ROD 1.0 J/pulse
  - 0.08 Nd:YAG, LASER SLAB 1.0 J/pulse
  - 0.05 SLOPE Ho:Tm:YAG mJ level

• LONG LIFETIME
  - $3.3 \times 10^9$ SHOTS PULSED
  - 30,000 HOURS CONTINUOUS WAVE
  - FACTOR OF 3 IN DAMAGE THRESHOLD, UV OPTICS

• TUNING
  - 0.68 - > 1.0 \( \mu \text{m} \) Ti:Al₂O₃
  - 0.72 - 0.81 \( \mu \text{m} \) Cr:BeAl₂O₄
  - 2.5 - 5.4 \( \mu \text{m} \) AgGaSe₂ OPO
  - 2.06 - 2.10 Ho:YLF, Ho:YAG
CURRENT PROGRAMS

• DOPPLER LIDAR
  - CO₂ GAS LASER
  - Ho:YLF SOLID-STATE LASER

• DIAL IN NEAR-INFRARED
  - Ti₃Al₂O₇
  - Cr:Be₃Al₂O₄

• DIAL IN MID-INFRARED
  - OPTICAL PARAMETRIC OSCILLATOR
  - RAMAN SHIFTING

• LASER RANGING

• DIODE DEVELOPMENT
  - SEED LASERS
  - DIODE LASER ARRAYS

AUGMENTED PROGRAMS

Instrument Demonstration

• Doppler LIDAR
• DIAL/Eyesafe DIAL
• Ranging/Altimetry

Technology Development

• In-Situ Lasers
• High-Energy Optics
• Receiver Technology
• Models/Spectroscopy
• Laser Diode Materials
• Scanning Lidar

*NEW PROGRAMS

Laws
Eagle
Glrs

Tunable, Single Wavelength
Damage Resistant Optics
Arrays/Amplifiers
Laser Design/New Materials
New Materials/Wavelength
Develop Scanning
**OBJECTIVE: GLOBAL WIND-SPEED MEASUREMENT**

<table>
<thead>
<tr>
<th>DOPPLER LIDAR</th>
<th>CO₂ LASER</th>
<th>Ho:YLF LASER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/Pulse</td>
<td>15 J</td>
<td>5-15 J</td>
</tr>
<tr>
<td>Pulse Repetition Frequency</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Linewidth</td>
<td>&lt; 0.2 MHz</td>
<td>&lt; 1.0 MHz</td>
</tr>
<tr>
<td>Pulsedlengh</td>
<td>~ 3.0 μsec</td>
<td>&gt; 0.6 μsec</td>
</tr>
<tr>
<td>Wavelength</td>
<td>9.1 μm</td>
<td>2.1 μm</td>
</tr>
<tr>
<td>Lead Center</td>
<td>MSFC</td>
<td>LaRC</td>
</tr>
</tbody>
</table>

**OBJECTIVE: GLOBAL MEASUREMENT OF ATMOSPHERIC CONSTITUENTS**

<table>
<thead>
<tr>
<th>DIAL/Eyesafe DIAL</th>
<th>Near-IR</th>
<th>Mid-IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/Pulse</td>
<td>1.0 J</td>
<td>1.0 J</td>
</tr>
<tr>
<td>Pulse-Repetition Frequency</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Tuning Range</td>
<td>0.7 - 1.0 μm</td>
<td>2.5 - 5.5 μm</td>
</tr>
<tr>
<td>Linewidth</td>
<td>1.0 pm</td>
<td>2.0 pm</td>
</tr>
<tr>
<td>Pulsedlengh</td>
<td>&lt; 0.3 μsec</td>
<td>&lt; 1.0 μsec</td>
</tr>
<tr>
<td>Lead Center</td>
<td>LaRC</td>
<td>LaRC</td>
</tr>
</tbody>
</table>
OBJECTIVE: TECTONIC PLATE MOTION, ICE CAP THICKNESS

Laser Ranging/Altimetry

- Nd:YAG
- Energy/Pulse: ~200 mJ total
- Pulse Repetition Frequency: 40 Hz
- Linewidth: 8.8 - 5.9 GHz
- Pulselength: 50 - 75 psec
- Wavelength: 1.06, 0.53, 0.35 μm

Streak Camera

- Demonstrate Resolution: 2.0 psec

Lead Center: GSFC

OBJECTIVE: DEVELOP DIODE SEED LASER AND LASER ARRAYS FOR PUMPING

<table>
<thead>
<tr>
<th>In-Situ Lasers/Seed Sources</th>
<th>Near-IR</th>
<th>Mid-IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>50 mW</td>
<td>50 mW</td>
</tr>
<tr>
<td>Linewidth</td>
<td>&lt; 30 MHz</td>
<td>&lt; 10 MHz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.73 μm</td>
<td>2.09 μm</td>
</tr>
<tr>
<td>Lifetime</td>
<td>50,000 hrs.</td>
<td>50,000 hrs.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laser Diode Materials/Pump</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power/Area</td>
<td>1500 W/cm²</td>
<td>1500 W/cm²</td>
</tr>
<tr>
<td>Linewidth</td>
<td>0.003 μm</td>
<td>0.003 μm</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.67 μm</td>
<td>1.63, 1.70 μm</td>
</tr>
<tr>
<td>Lifetime</td>
<td>5 × 10⁹ shots</td>
<td>5 × 10⁹ shots</td>
</tr>
</tbody>
</table>

Lead Center: JPL
OBJECTIVE: ENHANCE LASER RELIABILITY AND PERFORMANCE

High-Energy Optics
Increase in Energy Density
Database
Design Standards/Testing
Qualify Vendors/Techniques

1.06, near-IR, 2.1, mid-IR
2 times
LaRC database
Establish
Establish

Lead Center
LaRC

OBJECTIVE: DEVELOP IMPROVED DETECTION OF LIDAR SIGNALS

Receiver Technology
Type
Quantum Efficiency
Bandwidth
Elements
Integrated Amplifier

1.06/0.53
1.06/0.53
1.06/0.53
2.1
2.1
2.1

Emissive
Emissive
Emissive
PV
PV
PV

> 0.01/0.30
> 0.01/0.30
> 0.01/0.30
> 0.5
> 0.5
> 0.5

1.0 GHz
1.0 GHz
1.0 GHz
1-5 GHz
1-5 GHz
1-5 GHz

1
1
1
1 and 3 x 3
1 and 3 x 3
1 and 3 x 3

Dynodes
Dynodes
Dynodes
Electronic
Electronic
Electronic

Lead Center
Lead Center
Lead Center
GSFC
LaRC
LaRC

LaRC
LaRC
LaRC
OBJECTIVE: ANALYZE/PREDICT LASER MATERIALS/PERFORMANCE

• MODELS
  - QUANTUM MECHANICS
    ENERGY LEVELS, LIFETIMES
    ENERGY TRANSFER RATE
  - LASER MODEL
    2-D OSCILLATOR, TIME AND RADIAL COORDINATE
    OSCILLATOR WITH WAVELENGTH DISTRIBUTION

• SPECTROSCOPY, NEW MATERIALS
  - ENERGY LEVELS, LIFETIMES
  - TRANSFER RATES

• LEAD CENTER - LaRC

OBJECTIVE: DEVELOP LIGHT-WEIGHT, LOW-POWER SCANNING

SCANNER

SCAN ANGLE ± 2.5°
SCAN SPEED ~ 1.0 Hz
LIFETIME 50,000 hrs.
LEAD CENTER LaRC
# Flight Program Timetable

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Breadboard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler Lidar</td>
<td>CO₂</td>
</tr>
<tr>
<td></td>
<td>Ho:YLF</td>
</tr>
<tr>
<td>DIAL/Eyesafe Dial</td>
<td>Near-IR</td>
</tr>
<tr>
<td></td>
<td>Mid-IR</td>
</tr>
<tr>
<td>Laser Ranging</td>
<td></td>
</tr>
</tbody>
</table>

# Technology Programs Timetable

<table>
<thead>
<tr>
<th>Technology</th>
<th>Technology Demonstration</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Situ Lasers</td>
<td></td>
</tr>
<tr>
<td>Near-IR</td>
<td>1996</td>
</tr>
<tr>
<td>Mid-IR</td>
<td>1996</td>
</tr>
<tr>
<td>High-Energy Optics</td>
<td></td>
</tr>
<tr>
<td>1.06 µm</td>
<td>1995</td>
</tr>
<tr>
<td>Near-IR</td>
<td>1996</td>
</tr>
<tr>
<td>2.1 µm</td>
<td>1997</td>
</tr>
<tr>
<td>Mid-IR</td>
<td>1997</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
</tr>
<tr>
<td>1.06/0.53</td>
<td>1998/1996</td>
</tr>
<tr>
<td>2.1 µm</td>
<td>1995</td>
</tr>
<tr>
<td>Mid-IR</td>
<td>1997</td>
</tr>
<tr>
<td>Models/Spectroscopy</td>
<td></td>
</tr>
<tr>
<td>QM Model</td>
<td>1994</td>
</tr>
<tr>
<td>Laser Model</td>
<td>1996</td>
</tr>
<tr>
<td>Spectroscopy 2.1</td>
<td>1995</td>
</tr>
<tr>
<td>Diode Laser Materials</td>
<td></td>
</tr>
<tr>
<td>0.67 µm</td>
<td>1997</td>
</tr>
<tr>
<td>1.7 µm</td>
<td>1997</td>
</tr>
<tr>
<td>Scanner</td>
<td>1998</td>
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</table>
## FLIGHT PROGRAMS TASK AUGMENTATION 1993

<table>
<thead>
<tr>
<th>Program/Task</th>
<th>Centers</th>
<th>Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>MSFC</td>
<td>650</td>
</tr>
<tr>
<td>HO:YLF</td>
<td>LaRC</td>
<td>1550</td>
</tr>
<tr>
<td>DIAL/Eyesafe DIAL</td>
<td>LaRC</td>
<td>300</td>
</tr>
<tr>
<td>Near-IR</td>
<td>LaRC</td>
<td>600</td>
</tr>
<tr>
<td>Mid-IR</td>
<td>LaRC</td>
<td>300</td>
</tr>
<tr>
<td>Laser Ranging</td>
<td>GSFC</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>3400</td>
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</tbody>
</table>

## TECHNOLOGY DEVELOPMENT

<table>
<thead>
<tr>
<th>Program/Task</th>
<th>Flight Program</th>
<th>Center</th>
<th>Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Situ Lasers</td>
<td>LAWS</td>
<td>JPL</td>
<td>225</td>
</tr>
<tr>
<td>Diode Development</td>
<td>LAWS</td>
<td>LaRC</td>
<td>100</td>
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<tr>
<td>Frequency Swept</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>High-Energy Optics</td>
<td>All</td>
<td>LaRC</td>
<td>0</td>
</tr>
<tr>
<td>Receiver Technology 1.06/0.53</td>
<td>Ranging</td>
<td>GSFC</td>
<td>175</td>
</tr>
<tr>
<td>Mid-IR</td>
<td>LAWS</td>
<td>LaRC</td>
<td>200</td>
</tr>
<tr>
<td>Models/Spectroscopy Models</td>
<td>All</td>
<td>LaRC</td>
<td>100</td>
</tr>
<tr>
<td>Spectroscopy</td>
<td>LAWS</td>
<td>LaRC</td>
<td>200</td>
</tr>
<tr>
<td>Laser Diode Materials 0.67</td>
<td>DIAL</td>
<td>JPL</td>
<td>300</td>
</tr>
<tr>
<td>1.70</td>
<td>DIAL</td>
<td>JPL</td>
<td>300</td>
</tr>
<tr>
<td>Scanning LIDAR</td>
<td>All</td>
<td>LaRC</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>1600</td>
</tr>
</tbody>
</table>
SUMMARY

- REMOTE SENSORS MONITOR HEALTH OF PLANET EARTH
- FEASIBILITY DEMONSTRATED ON BASE PROGRAM
- AUGMENTATION NEED FOR TIMELY DEPLOYMENT

<table>
<thead>
<tr>
<th>Technology Element: Laser Sensors ($K (NET))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-Element Resources:</strong></td>
</tr>
<tr>
<td>Eye-Sate Doppler Lidar</td>
</tr>
<tr>
<td>1934  5000  1935  5000  1936  5000  1937  5000  1938  5000  1939  5000  2000  5000</td>
</tr>
<tr>
<td>DIAL/Eye-Sate DIAL</td>
</tr>
<tr>
<td>1934  2500  1935  5000  1936  5000  1937  2250  1938  2500  1939  2500  2000  2500</td>
</tr>
<tr>
<td>Ranging/Atmospy</td>
</tr>
<tr>
<td>1934  1000  1935  1500  1936  2000  1937  2250  1938  2500  1939  2500  2000  2500</td>
</tr>
<tr>
<td>In-Situ Laser</td>
</tr>
<tr>
<td>High-Energy Optics</td>
</tr>
<tr>
<td>Receiver Technology</td>
</tr>
<tr>
<td>1934  1000  1935  1000  1936  1000  1937  1000  1938  1000  1939  1000  2000  1000</td>
</tr>
<tr>
<td>Models/Spectroscopy</td>
</tr>
<tr>
<td>1934  800  1935  800  1936  800  1937  800  1938  800  1939  800  2000  800</td>
</tr>
<tr>
<td>Laser Dode Materials</td>
</tr>
<tr>
<td>1934  1000  1935  1500  1936  2250  1937  2250  1938  2250  1939  2250  2000  2250</td>
</tr>
<tr>
<td>Scanning Lidar</td>
</tr>
<tr>
<td>1934  700  1935  1200  1936  2200  1937  2200  1938  4000  1939  4000  2000  4000</td>
</tr>
<tr>
<td><strong>Sub-Element Totals:</strong></td>
</tr>
<tr>
<td>1934  14500  1935  19600  1936  21750  1937  22250  1938  24300  1939  24300  2000  24300</td>
</tr>
</tbody>
</table>
PASSIVE MICROWAVE SENSING

PROJECT SUMMARY

SCIENCE SENSING PROGRAM AREA
OF THE
SPACE SCIENCE TECHNOLOGY PROGRAM

June 27, 1991

Office of Aeronautics, Exploration and Technology
National Aeronautics and Space Administration
Washington, D.C. 20546

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

PASSIVE MICROWAVE SENSING

TECHNOLOGY NEEDS

THE PASSIVE MICROWAVE SENSOR TECHNOLOGY PROGRAM WILL OVERCOME MAJOR LIMITATIONS OF TODAY'S PASSIVE MICROWAVE SENSORS (SPATIAL AND TEMPORAL RESOLUTION, ACCURACY). ENHANCE AND ENABLE THE OPERATION OF HIGH RESOLUTION MICROWAVE IMAGERS FROM LOW-EARTH AND GEOSYNCHRONOUS ORBITS.

PROVIDE COMPLEMENTARY MEASUREMENTS OF THE EARTH'S VITAL SIGNS, INCLUDING:

• EARTH OBSERVING SYSTEM (EOS) PASSIVE MICROWAVE SENSORS
  - ADVANCED MICROWAVE LIMB SOUNDER (2006)
• GEOSTATIONARY PLATFORM (2005)
  - LOW FREQUENCY RADIOMETER (6 - 60GHz)
  - HIGH FREQUENCY RADIOMETER (60 - 220GHz)

PROVIDE COMPLEMENTARY MEASUREMENTS FOR ASTROPHYSICS AND SPACE SCIENCE INVESTIGATIONS, INCLUDING:

• COSMIC BLACKBODY RADIATION OF UNIVERSE
  - ANISOTROPY SATELLITE RADIOMETER (ADVANCED COBE), (40-90 GHz) (ΔT = 6μK)
• GALACTIC RADIO ASTRONOMY-VERY LONG BASELINE INTERFEROMETER (VLBI)
  - 25 METER RADIO TELESCOPE IN SPACE
TECHNOLOGY DEVELOPMENT CHALLENGES

- Extend measurement to:
  - Smaller resolution cell size (footprint <10km)
  - Extended swath width coverage

- Improved absolute accuracy of measurements (0.1→0.5K)
  - Develop in-space calibration methodology
  - Improve radiometer front-end sensitivities

TECHNOLOGY DEVELOPMENT APPROACH

- Development of large aperture erectable deployable reflector antenna systems (10 - 220GHz)

- Research and development of synthetic aperture systems for low frequency (1 - 6GHz) radiometer applications

- Focused development of in-space calibration techniques for filled and unfilled aperture radiometers

- Development of low-noise amplifiers (HEMT) at frequencies to 220GHz

- Development of low-loss mic components for 10 - 220 GHz radiometer front-ends

STATE OF THE ART ASSESSMENT

- Electronic scanning techniques for field aperture
  - No electronic scanning radiometer using a reflector has been used in space. ESMR (phased array) is the SOA

- MMIC technology for radiometer phased array feed system
  - Phased array technology for remote sensing is lagging communications technology
  - LNA technology demonstrated at 118GHz

- Synthetic aperture radiometer technology
  - Conceptual studies conducted
  - L-band array, aircraft flight tests demonstrated (ESTAR)

- Precision membrane reflector antenna technology (<40GHz)
  - Technology demonstrated for diameters up to 15-meters at frequencies up to 12GHz (possibly 20 - 30GHz with improved mesh)
  - Operational systems at 5-meter diameter, 20GHz

- Wide scanning precision reflector for 40 - 220GHz
  - Multiple beam antenna technology demonstrated for 20/30Ghz solid reflector
  - Launch of satellite planned 1992 for 20/30GHz reflector
  - Solid aperture 4 - 5 meters without scanning
Distributed phased-array technology 40 - 220GHz
- Phased-array technology developed for military applications but further development needed for LSA's

Rapid scanning ant. dev.
- Conceptual studies on 5-meter conical scan reflector for use in low Earth orbit

Computer-aided software engineering
- Numerous EM analysis techniques (physical optics, GTD MOM, etc.) but limited end-to-end analysis for LSA

Large space antenna calibration and test methodology
- Near field tests of 15-meter, mesh deployable antenna at 12GHz (1985)
- Near field tests of Magellan spacecraft (X-band) (1989)
- Study completed for extending near field capability to 60GHz (1989)

Current Program

- CODE RC
  - ADAPTIVE FEED COMPENSATION ON 15-M HOOP/COLUMN ANTENNA
  - VIVALDI FEED ANALYSIS AND LAB. STUDY
  - LOW-NOISE RADIOMETER COMPONENTS STUDIES
  - RADIOMETER BEAM EFFICIENCY REQUIREMENTS STUDIES
  - RADIOMETER ARRAY FEED PRELIMINARY STUDY
  - END-TO-END RADIOMETER SYSTEMS STUDY

- CODE RM
  - GEOSTATIONARY LARGE ANTENNA CONFIGURATION CONCEPT DESIGN
  - DEPLOYABLE ANTENNA CONFIGURATION CONCEPTS (25-M CLASS)
  - ERECTABLE ANTENNA CONFIGURATION STUDIES/DEVELOPMENT
  - THERMAL ANALYSIS CODE DEVELOPMENT FOR LARGE MESH-DEPLOYABLE ANTENNAS
LARGE SPACE ANTENNA CAPABILITY
DEMONSTRATED FOR SELF-CORRECTION IN SPACE

Calculated E-plane Radiation Patterns
Before Surface Adjustment  After Surface Adjustment  Surface Adjustment With Feed Compensation

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING
PASSIVE MICROWAVE SENSING

Focused Technology Performance Objectives

<table>
<thead>
<tr>
<th>Earth Science Observable</th>
<th>Freq. (GHz)</th>
<th>Spatial Resolution (km)</th>
<th>Radiometric Temperature (Minimum T K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Requirement</td>
<td>Goal</td>
</tr>
<tr>
<td>Precipitation over ocean</td>
<td>19</td>
<td>1 - 30</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>1 - 30</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>50 - 60</td>
<td>1 - 30</td>
<td>6</td>
</tr>
<tr>
<td>Precipitation over land</td>
<td>37</td>
<td>1 - 30</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>50 - 60</td>
<td>1 - 30</td>
<td>6</td>
</tr>
<tr>
<td>Water vapor*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>19</td>
<td>5 - 20</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>5 - 20</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>5 - 20</td>
<td>8</td>
</tr>
<tr>
<td>Profile</td>
<td>22</td>
<td>5 - 20</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>5 - 20</td>
<td>8</td>
</tr>
<tr>
<td>Temperature profile</td>
<td>22</td>
<td>5 - 20</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>5 - 20</td>
<td>8</td>
</tr>
<tr>
<td>Surface wind speed</td>
<td>19</td>
<td>10 - 50</td>
<td>16</td>
</tr>
<tr>
<td>Cloud base height</td>
<td>35 Active</td>
<td>5 - 25</td>
<td>N/A</td>
</tr>
<tr>
<td>Cloud water content**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Over ocean)</td>
<td>19</td>
<td>1 - 30</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>1 - 30</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>1 - 30</td>
<td>8</td>
</tr>
<tr>
<td>Atmospheric winds profile</td>
<td>37 Active</td>
<td>50</td>
<td>N/A</td>
</tr>
<tr>
<td>Snow Cover</td>
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* Requires all three frequencies
** Requires two of the three frequencies

SE5-4
PASSIVE MICROWAVE SENSING

TECHNOLOGY ROADMAP/SCHEDULE

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<td>• Innovative sensor device</td>
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<td>• Sensor support tech.</td>
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</table>

OTHER DEVELOPMENT EFFORTS

- RADIOMETER MMIC DEVELOPMENT (ITT/MARTIN MARIETTA) (DARPA FUNDED MMIC TECHNOLOGY DEVELOPMENT)
- INFLATABLE REFLECTOR FLIGHT EXPERIMENT - L'GARDE INC. (CODE RX IN-STEP EXPERIMENT)
- ROME AIR DEVELOPMENT OF SPACE FED LENS AT GRUMMAN (S-BAND TEST OF 20 FT. LENS)
- ADVANCED SUNFLOWER ANTENNA DEVELOPMENT (IR&D BY TRW)
- 94GHz LNA/MIXER (INTEGRATED MODULE) AT TRW
- LINEAR TAPERED SLOT, DUAL-NOTCH ANTENNA (TRW, UMASS, NCSU)
- CORRELATION RADIOMETER CONCEPT DEVELOPMENT AT UNIV. OF MASS.
PASSIVE MICROWAVE SENSING

AUGMENTED PROGRAM

- SYNTHETIC APERTURE MICROWAVE RADIOMETER
  - TECHNOLOGY FOR LEO - ESTAR
  - STUDIES FOR GEO

- PRECISION, MEMBRANE REFLECTOR ANTENNA (<40GHz)
  - LEO & GEO
  - DIAMETERS TO 25 METERS

- PRECISION SOLID REFLECTOR ANTENNA
  - 37 - 220GHz
  - GEO - 4 METERS TO LARGER

- PHASED-ARRAY ELECTRONIC STEERING
  - < 40GHz
  - LEO OR GEO

- MMIC RADIOMETER COMPONENT TECHNOLOGY
  - INTEGRATED FEED HEMT LNA
  - CRYOGENIC HEMT

- RADIOMETER MEASUREMENT AND CALIBRATION

- QUASI-OPTICAL COMPONENTS (BEAM FORMING NETWORKS)

PRELIMINARY FY'93 AUGMENTATION - PRIORITIZATION

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<tr>
<th>PRIORITY</th>
<th>ITEM</th>
<th>FUNDING (M$)</th>
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<td>Digital correlation spectrometer</td>
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**Program Critical Milestones**

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<td>(1) Large Aperture, Wide Scanning Antenna Development</td>
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<td>(2) Microwave Radiometer Concept(s) Development</td>
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<td><strong>Augmentation Program - Major Elements</strong></td>
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<td>(1) Synthetic Aperture Radiometer Development</td>
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<td>(2) Precision Filled Aperture Antenna Technology (Membrane and solid reflector)</td>
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<td>(3) Phased Array, Electronic Scanning Technology</td>
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<td>(4) MMIC Radiometer Components</td>
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<td>(5) Radiometer/Antenna Measurement &amp; Calibration</td>
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<td>(6) Supporting Component Technologies (Quasi-optical and Piezoelectric)</td>
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**Passive Microwave Sensor Technology**

**FY’93 Obligation Plans**
**Estimated Funding Guideline $4.0M**

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<tr>
<th>Technology Research Areas</th>
<th>Costing Method</th>
<th>Funding Amount FY’93</th>
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<tbody>
<tr>
<td><strong>Research Level</strong></td>
<td>University grants (Ga. Tech., U. Mass., ODU, UVA)</td>
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<tr>
<td>- University research (Atmospheric and surface science, synthetic aperture research)</td>
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<td>- Industry/government (Radiometer designs)</td>
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<td><strong>Device Level Technologies</strong></td>
<td>Industry Contracts (Existing task assignment contracts)</td>
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<td>- MMIC radiometers (HEMT LNA, receiver arrays, limiters/filters)</td>
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<td>- Beam forming devices</td>
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<td><strong>Subsystem Level Technologies</strong></td>
<td>NASA In-house fabrication</td>
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<td>- Phased array, wide scanning network</td>
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<td>- Subscale aperture/near field system</td>
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<td>- Radiometer measurement/calibration</td>
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<tr>
<td><strong>System Integration Technologies</strong></td>
<td>In-house radiometer evaluation</td>
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<td>- Integrated reflector system evaluation</td>
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<td>- Integrated radiometer system evaluation</td>
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<td>- Aircraft remote sensing evaluations</td>
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<td>Total</td>
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* FY’93 development contracts awarded
ACTIVE MICROWAVE SENSOR TECHNOLOGY PROJECT SUMMARY

OBSERVATORY SYSTEMS PROGRAM AREA OF THE SPACE SCIENCE TECHNOLOGY PROGRAM

JUNE 27, 1991

Office Of Aeronautics, Exploration And Technology
National Aeronautics And Space Administration
Washington, D.C. 20546

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS
ACTIVE MICROWAVE SENSORS

TECHNOLOGY NEEDS

• THE ACTIVE MICROWAVE SENSORS TECHNOLOGY PROGRAM WILL SUPPORT THE FULL RANGE OF SPACE RADAR SCIENCE INSTRUMENT TECHNOLOGY NEEDS, INCLUDING:

  • EARTH OBSERVING SYSTEMS (EOS)
    • EOS SYNTHETIC APERTURE RADAR (L-, C-, X- BANDS, QUAD POLARIZATION)
    • EOS SCATTEROMETER (SCANSCAT)

  • TOPOGRAPHICAL MISSIONS
    • TOPSAT RADAR ALTIMETER (Ka-BAND INTERFEROMETER)

  • METEOROLOGICAL RADAR MISSIONS
    • RAIN RADAR (X-, Ka BANDS, LEO)
    • GEOSTATIONARY RAIN RADAR (Ka, W Band)

  • ADVANCED PLANETARY RADAR MAPPERS
    • LUNAR SOUNDERS (<P-BAND), MARS LANDER (Ka-BAND)
EOS SAR OVERVIEW

- **SAR PROVIDES DIRECT MEASUREMENT OF SURFACE ROUGHNESS AND DIELECTRIC CONSTANT**
- **MULTIPLE SIMULTANEOUS MEASUREMENTS AT DIFFERENT POLARIZATIONS AND FREQUENCIES PROVIDE INDEPENDENT CHARACTERIZATIONS OF THE SURFACE (SUBSURFACE) PROPERTIES**
  - POLARIZATION DATA CONTAINS DETAILED SCATTERING INFORMATION
- **KEY GEOPHYSICAL MEASUREMENTS**
  - SOIL MOISTURE (e.g., VOLUMETRIC WATER CONTENT)
  - BIOMASS (e.g., FOREST CANOPY DENSITY)
  - OCEAN WAVES (e.g., WAVE HEIGHT AND DIRECTION)
  - POLAR ICE (e.g., CONCENTRATION, VELOCITY)

EOS SAR TECHNOLOGY CHALLENGES

**FLIGHT SYSTEM**
- **INSTRUMENT** (20 m x 4.5 m)
  - LIGHT WEIGHT MATERIALS (25 kg/m²)
  - COMPACT/DEPLOYABLE STRUCTURES
  - MECHANISMS
  - CONFORMAL ARRAY DESIGNS
- **RF ELECTRONICS**
  - MMC COMPONENTS
  - HIGH EFFICIENCY (50%), HIGH YIELD TR MODULES, PHASE SHIFTERS
  - MODULE LAYOUTS, CONTROL SYSTEMS
- **DIGITAL ELECTRONICS**
  - INTEGRATED ELECTRONICS (>100 MHz) (ASIC TECHNOLOGY)
  - SIGNAL PROCESSOR
  - ON-BOARD REAL-TIME SAR PROCESSOR
  (REDUCE DOWNLINK DATA RATE BY FACTOR OF 10)

**GROUND SYSTEM**
- **IMAGE CORRELATOR**
  - ADVANCED ARCHITECTURES
  - HIGH THROUGHPUT, PRECISION, FLEXIBILITY
  - ADVANCED ALGORITHMS
  - POLARIMETRY, SCANSAR
- **POST PROCESSOR**
  - GEOPHYSICAL INFORMATION EXTRACTION
  - VISUALIZATION, AI, NEURAL NETWORKS
- **GROUND CALIBRATION DEVICES**
  - TRANSPONDERS - LOW COST, COMPACT, DEPLOYABLE
MICROWAVE INTERFEROMETER MEASURES RELATIVE PHASE OF PULSE ECHO USING TWO ANTENNAS AT SLIGHTLY DIFFERENT VIEWING GEOMETRIES

- RELATIVE PHASE PROVIDES INFORMATION ON SURFACE TOPOGRAPHY

TOPSAT MISSION WILL PROVIDE COMPLETE GLOBAL COVERAGE WITHIN ONE YEAR AT SPATIAL RESOLUTION OF 30 m AND HEIGHT ACCURACY OF 2 m

SCIENCE APPLICATIONS
- GEOLOGY
- HYDROLOGY
- GEOMORPHOLOGY
ADVANCED RAIN RADAR OVERVIEW

- RAIN RADAR MEASURES RETURN ECHO POWER VERSUS ECHO DELAY TIME
- DERIVES 3-DIMENSIONAL RAINFALL MEASUREMENTS
- LOW EARTH ORBITING SYSTEM WITH ELECTRONIC BEAM SCANNING
- PROVIDES WIDE SWATH COVERAGE AT ~ 5 km SPATIAL RESOLUTION
- GEOSTATIONARY PLATFORM
  - LONG-TERM, NEAR CONTINUOUS OBSERVATIONS
  - RAIN/CLOUD COLUMNAR HEIGHT STUDIES
- HIGH FREQUENCY RADAR DESIGNS (15-90 GHz)
- IMPROVED SNR, RESOLUTION

ADVANCED RADAR TECHNOLOGY

- RAIN RADAR TECHNOLOGY CHALLENGES

- FLIGHT SYSTEM
  - 10 M DIAMETER @ 90 GHz
  - SURFACE DISTORTION COMPENSATION
  - POINTING ACCURACY, MUTUAL COUPLING
  - BEAM WAVEGUIDE
- RF ELECTRONICS
  - COMPONENTS AT 90 GHz
  - LOW LOSS PHASE SHIFTERS, SWITCHES AND CIRCULATORS
  - LOW NOISE RECEIVERS (≤ 4 dB)
  - HIGH POWER TRANSMITTERS (> 600W)
  - MIC COMPONENTS (DISTRIBUTED ARRAY)
- DIGITAL ELECTRONICS
  - ASIC DIGITAL SYSTEMS
- CALIBRATION
  - BUILT-IN TEST EQUIPMENT FOR HIGH PRECISION PHASE CHARACTERIZATION
- GROUND SYSTEM
  - SIGNAL PROCESSOR
    - RAIN RATE EXTRACTION ALGORITHMS
    - ALGORITHM DEVELOPMENT FOR PHASE CALIBRATION
TECHNOLOGY CHALLENGES/APPROACH

TECHNOLOGY DEVELOPMENT CHALLENGES:
DECREASE MASS, POWER CONSUMPTION AND OVERALL COST; ENHANCE PERFORMANCE OF MILLIMETER WAVE SPACE RADARS FOR REMOTE SENSING

SPECIFIC CHALLENGES INCLUDE:
- INCREASE EFFICIENCY OF TRANSMIT/RECEIVE MODULES USING DISTRIBUTED ACTIVE ARRAYS
- MMIC COMPONENTS, CROSS-ANTENNA AMPLITUDE AND PHASE CALIBRATION
- REDUCE MASS, VOLUME AND COST OF DIGITAL CONTROL AND PROCESSING SYSTEMS
- ASIC COMPONENTS, LARGE DATA VOLUMES, HIGH RATES, HIGH COMPUTATIONS
- REDUCE STRUCTURE MASS AND INCREASE SURFACE ACCURACY
- COMPOSITE MATERIALS, ADAPTIVE PHASE COMPENSATION, CONFORMAL ARRAYS

TECHNOLOGY DEVELOPMENT APPROACH

FOCUSED DEVELOPMENT OF BREADBOARD RADAR SUBSYSTEMS
1-10 GHZ LARGE ARRAY PERFORMANCE, CALIBRATION AND CONTROL ISSUES
BASE RESEARCH IN MILLIMETER WAVE DEVICES, STRUCTURES AND CALIBRATION TECHNOLOGY
35-90 GHZ COMPONENTS (MMIC AND NON-MMIC), LARGE ACCURATE COMPOSITE STRUCTURES

STATE OF THE ART ASSESSMENT

GENERAL ASSESSMENT:
CURRENT TECHNOLOGY LIMITS PERFORMANCE IN 1-10 GHZ MICROWAVE ACTIVE SENSORS; MILLIMETER WAVE (35-90 GHZ) TECHNOLOGY DEVELOPMENT REQUIRED TO ENABLE MILLIMETER WAVE RADAR SENSORS

DETAILED ASSESSMENT OF NASA PROGRAM:
SIR-C RADAR HAS BEEN UNDER DEVELOPMENT SINCE 1986 USING DISCREET MICROWAVE AND DIGITAL COMPONENTS (1.2, 5.3 GHZ); DISTRIBUTED ACTIVE ARRAY
OAET DEVELOPMENT OF MMIC DEVICES AT LeRC
- APPLICATIONS ARE COMMUNICATIONS ORIENTED (15-50 GHZ), LNA (3.5-4 DB), MIXER AT 94 GHZ
OSO MMIC ARRAY DEVELOPMENT AT JPL AT 32 GHZ; OSSA 30 GHZ ARRAY AT LeRC
- GOAL: 15-20 ELEMENT SCANNING ARRAY, DEVELOP ELEMENT FEED/CONTROL TECH.
SURFACE DISTORTION COMPENSATION - GROUND ALIGNMENT, COMPUTER CONTROLLED (LeRC - 15M, JPL - 5M GALILEO)
SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS
ACTIVE MICROWAVE SENSORS

RADAR TECHNOLOGY PERFORMANCE OBJECTIVES

<table>
<thead>
<tr>
<th>PERFORMANCE REQUIREMENT</th>
<th>Current SOA SIR-C</th>
<th>EOS-B SAR</th>
<th>Topographic Radar</th>
<th>Rain Radar (Geostationary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Size</td>
<td>12 X 4 M</td>
<td>16 X 4 M</td>
<td>2 - 5.5 X 0.4 M</td>
<td>10M Diameter</td>
</tr>
<tr>
<td>Frequency</td>
<td>1.3,5,3,9.6 GHz</td>
<td>1.3,5,3,9.6 GHz</td>
<td>35 GHz</td>
<td>35,94 GHz</td>
</tr>
<tr>
<td>Antenna Structure</td>
<td>Aluminum</td>
<td>Composite</td>
<td>Composite</td>
<td>Composite</td>
</tr>
<tr>
<td>Surface Accuracy</td>
<td>0.5 cm</td>
<td>0.5 cm</td>
<td>0.1 cm</td>
<td>0.03 cm</td>
</tr>
<tr>
<td>Antenna Mass</td>
<td>75 kg/m²</td>
<td>&lt; 20 kg/m²</td>
<td>&lt; 5 kg/m²</td>
<td>&lt; 1 kg/m²</td>
</tr>
<tr>
<td>Peak Power</td>
<td>9 kW</td>
<td>&gt; 10 kW</td>
<td>&gt; 0.5 kW</td>
<td>&gt; 2 kW</td>
</tr>
<tr>
<td>Calibration Error</td>
<td>- 2-3 dB</td>
<td>&lt; 1.5 dB, 10° rms</td>
<td>&lt;1 dB, 3° rms</td>
<td>&lt; 0.5 dB</td>
</tr>
<tr>
<td>Approximate Need Date</td>
<td>-</td>
<td>1996</td>
<td>1998</td>
<td>1999</td>
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</table>

TECHNOLOGY DEVELOPMENT FOR SPACEBORNE RADARS

JPL

ANTENNA: KEY SAR TECHNOLOGY AREA

- SIR-C* AND Eos SAR UTILIZE DISTRIBUTED PHASED ARRAY TECHNOLOGY WITH MULTIPLE TRANSMIT/RECEIVE MODULES ACROSS ANTENNA APERTURE
- BEAM SCANNING, GRACEFUL SYSTEM DEGRADATION, DISTRIBUTED (LOW) RF POWER

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>SIR-C</th>
<th>BASELINE Eos SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANTENNA SIZE</td>
<td>12 x 4 m</td>
<td>10.9 x 2.6 m</td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>L/C BANDS</td>
<td>L/C/X-BANDS</td>
</tr>
<tr>
<td>ANTENNA STRUCTURE</td>
<td>ALUMINUM</td>
<td>GRAPHITE EPOXY/HONEYCOMB</td>
</tr>
<tr>
<td>ANTENNA MASS</td>
<td>3263 kg</td>
<td>505 kg</td>
</tr>
<tr>
<td>No. T/R MODULES</td>
<td>252(L), 504(C)</td>
<td>192(L), 192(C), 384(X)</td>
</tr>
<tr>
<td>MAX PWR PER T/R MODULE</td>
<td>41 W(L), 10 W(C)</td>
<td>50 W(L), 15 W(C), 10 W(X)</td>
</tr>
<tr>
<td>ELECTRONICS WEIGHT</td>
<td>557 kg</td>
<td>330 kg</td>
</tr>
<tr>
<td>T/R MODULE TECHNOLOGY</td>
<td>HYBRID</td>
<td>HYBRID</td>
</tr>
</tbody>
</table>

- SIR-C/XSAR COMBINED: WEIGHT -5900 kg; PEAK POWER -9 kW
- Eos SAR BASELINE: WEIGHT -1300 kg; PEAK POWER -5.8 kW

- SIGNIFICANT SPACECRAFT RESOURCE CONSUMPTION
- C/X-BAND DESCOPED TO DUAL POLARIZATION TO REDUCE WEIGHT/POWER - SCIENCE IMPACT

* XSAR USES SINGLE TRANSMITTER/RECEIVER APPROACH, NO BEAM SCANNING
TECHNOLOGY DEVELOPMENT FOR SPACEBORNE RADARS
COMPARISON OF Eos-B & PRESENT BASELINE Eos SAR STOW CONFIGURATION

**Eos-B**
- **ANTENNA SIZE** - 16 m x 4 m
- **ORBITAL ALTITUDE** - 705 km

**BASELINE Eos SAR**
- **ANTENNA SIZE** - 10.9 m x 2.6 m
- **ORBITAL ALTITUDE** - 620 km

**TOPSAT**
Strawman System Parameters

- **Frequency**
- **Transmit Power**
- **Total Instrument Power**
- **Total Instrument Weight**
- **Pulse Length**
- **Bandwidth**
- **PRF**
- **Pulse Timing**
- **Antenna Size**
- **Antenna Beamwidths**
- **Antenna Peak Gain**
- **p Range**
- **Transmit Loss**
- **Receive Loss**
- **Atmospheric Loss (2 way)**
- **Antenna Temperature**
- **Receiver Noise Figure**
- **Dynamic Range**
- **Data Rate into recorder (tracking)**

- 35 GHz
- 250 W
- 480 W
- 550 kg
- 85 ns
- 24.2 MHz
- 3.88 kHz
- inerleave mode
- 0.4 m x 5.5 m
- 0.9" x 1.2"
- 52 dB
- -15 to +7 dB
- 2.5 dB
- 1.0 dB
- 2.0 dB
- 290 K
- 4 dB
- 22 dB
- 96 Mbps

SE6-7
HEIGHT SENSITIVITY TO CHANGES IN SNR

INCREASED SNR FROM NOMINAL SNR (10 dB) MAY SIGNIFICANTLY IMPROVE PERFORMANCE. HOWEVER, A 5 dB DROP IN SNR, DEGRADES THE PERFORMANCE BY ALMOST 100%.

JPL

TOPSAT ATTITUDE AND ARTICULATION CONTROL SUBSYSTEM REQUIREMENTS AND CAPABILITIES

REQUIREMENTS

ATTITUDE KNOWLEDGE ACCURACY (DEG)

<table>
<thead>
<tr>
<th></th>
<th>ROLL</th>
<th>YAW</th>
<th>PITCH</th>
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<tbody>
<tr>
<td>REQUIREMENTS</td>
<td>0.0003</td>
<td>0.01</td>
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</table>

CONTROL ACCURACY (DEG)

<table>
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<th>PITCH</th>
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<tbody>
<tr>
<td>REQUIREMENTS</td>
<td>0.01</td>
<td>0.1</td>
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</table>

BASELINE KNOWLEDGE ACCURACY

100 microns
**TECHNOLOGY DEVELOPMENT FOR SPACEBORNE RADARS**

**GEOSTATIONARY RAIN RADAR**

- **GEOSTATIONARY RAIN RADAR (GRR) - '98 START**
  - Scientific need for continuous, long term precipitation measurements from geostationary orbits
  - 2-frequency operation to extend rain-rate measurement range - 35/94 GHz

- **STRAWMAN SYSTEM PARAMETERS**
  - Peak transmit power: 1 kW
  - Pulse width: 200 µs
  - Bandwidth: 600 kHz
  - Antenna diameter: 10 m
  - Horizontal resolution: 35 km (@ 35 GHz); 15 km (@ 94 GHz)

**NEAR-EARTH ORBITING CLOUD RADAR**

- **COMPARISON OF 35 AND 94 GHz FOR CLOUD COLUMNAR HEIGHT STUDIES:**
  - Cloud reflectivity $\propto f^4$
  - 17-dB brighter for cloud-reflected signals at 94 GHz
  - Cloud absorptions at both frequencies are small (< 0.5 dB/km) for "Dry" clouds (liquid-water content < 0.1 g/m$^3$)

- **STRAWMAN NEAR-EARTH ORBITING CLOUD PROFILING RADAR AT 94 GHz -2000 NEW START**
  - Altitude = 400 km
  - Transmit peak power = 2 kW
  - Pulse width = 200 µs
  - Bandwidth = 1 MHz
  - Antenna diameter = 10 m

- **ESTIMATED RADAR PERFORMANCE**
  - Vertical resolution = 150 m; horizontal resolution = 130 m
  - SNR for radar return from cloud base given in table below

<table>
<thead>
<tr>
<th>CLOUD TYPE</th>
<th>CLOUD THICKNESS</th>
<th>CLOUD WATER CONTENT (g/m$^3$)</th>
<th>SNR (dB)</th>
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</thead>
<tbody>
<tr>
<td>STRATUS</td>
<td>0.5</td>
<td>0.2 - 0.4</td>
<td>+11.9</td>
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<tr>
<td>NIMBOSTRATUS</td>
<td>3.0</td>
<td>0.2 - 0.9</td>
<td>+2.6</td>
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<tr>
<td>CUMULONIMBUS</td>
<td>3.0</td>
<td>0.4 - 8.0</td>
<td>+5.0</td>
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<tr>
<td>CIRRIFORM (ICE)</td>
<td>2.0</td>
<td>0.02 - 0.1</td>
<td>+24.3</td>
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</tbody>
</table>
SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

ACTIVE MICROWAVE SENSORS

OTHER DEVELOPMENT EFFORTS

- DARPA MMIC PROGRAM
  - *INCREASE DEVICE YIELD (DECREASE UNIT COST) FOR 1-10 GHZ*

- DARPA TRAVELING WAVE TUBE (TWT) INITIATIVE
  - ECM APPLICATIONS (WIDE BANDWIDTH), COMPACT HIGH EFFICIENCY COMPONENTS ≤ 94 GHz

- AIR FORCE SPACE-BASED WIDE AREA SURVEILLANCE PROGRAM AND SPACE-BAND RADAR PROGRAM HAVE BEEN RESTRUCTURED INTO PROGRAM CALLED NEXT GENERATION RADAR
  - EMPHISIS PRIMARILY ON L- AND S- BAND MMIC PHASED ARRAY DEVELOPMENT
  - FIRST ARRAY TEST SCHEDULED FOR 97-98 TIME FRAME
**Advanced L-Band T/R Module (ALMOD)**

### Parameter | Performance
--- | ---
Frequency | 1.2 - 1.4 GHz
Bandwidth | 15% / 10 MHz
Power Output | 5 watts peak
Duty Factor | 50% max
Transmit/Receive Gain | 30 dB min
Power Added Efficiency | 35% min
Noise Figure | 2.5 dB max
Phase Shifter Bits/Accuracy | 5 / ± 3 deg
Gain Control | 15 dB / 64 steps
Size | 1" x 2" x 0.5"
Weight | 13 grams
ACTIVE MICROWAVE SENSORS

STRATEGIC PROGRAM DESCRIPTION AND JUSTIFICATION
RADAR ACTIVE SENSOR TECHNOLOGY DEVELOPMENT

DESCRIPTION:
This effort will lead to the development of light weight, conformal array designs utilizing MMIC transmit/receive modules operating between 0.5 - 35 GHz and development of advanced digital correlators incorporating high throughput, precision and improved flexibility with advanced polarimetry and scanner algorithms.

JUSTIFICATION:
Radar synthetic aperture active sensors (0.5 - 10 GHz) provide global measurements of soil moisture, biomass, ocean waves and polar ice with spatial resolution of 10 - 30 m. Microwave interferometers (15 - 35 GHz) are capable of geology, hydrology and geomorphology measurements with spatial resolution of 30 m. Advanced rain radar (15 - 35 GHz) will provide long-term, near continuous observations of rain and cloud columnar heights with spatial resolution of the order of 5 km.

This technology will result in lower cost, mass and power consumption of lower frequency radar systems and will enable millimeter wave radar systems. Processor development work will result in greater science data return and throughput. The focus will be on light weight materials and compact structures incorporating highly integrated digital and microwave components. In addition, higher frequency (35 - 35 GHz), higher power (250 - 600 W, peak power) and higher efficiency (> 35%) radar electron beam devices will be developed.

ACTIVE MICROWAVE SENSORS
FY93 3X PROGRAM PRIORITIZATION

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

1) MMIC ACTIVE ARRAY PROTOTYPE (1-10 GHz), A/C DEMONSTRATION
   • CENTERS: JPL
   • MISSIONS: EOS SAR
   • TIMEFRAME: 1993-1996
   • AUGMENTED (3X) FUNDING: $3.9M

2) 35 GHz TRANSMITTER COMPONENT AND DISTRIBUTED PHASED ARRAY DEVELOPMENT (TWTA SOLID STATE - 500W @ 35% EFFICIENCY)
   • CENTERS: JPL, LARC
   • MISSIONS: TOPOGRAPHY MAPPER SATELLITE (TOPSAT)
   • TIMEFRAME: 1993-1997
   • AUGMENTED (3X) FUNDING: $3.0M (STRATEGIC FUNDING: $12.3)

3) CALIBRATION SUBSYSTEM FOR ACTIVE PHASE ARRAY ANTENNAS (MODULE AND ARRAY LEVEL)
   • CENTERS: JPL, LARC
   • MISSIONS: EOS SAR, TOPSAT, RAIN RADAR
   • TIMEFRAME: 1993-1999
   • AUGMENTED (3X) FUNDING: $2.2M (STRATEGIC FUNDING: $3.9)
ACTIVE MICROWAVE SENSORS
FY93 3X PROGRAM
PRIORITIZATION (continued)

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

4) 94 GHz COMPONENT DEVELOPMENT (TWTA) - 600W, 30% EFFICIENT) AND ANTENNA ASSEMBLY PROTOTYPE
   • CENTERS: LaRC, JPL
   • MISSIONS: RAIN RADAR
   • TIMEFRAME: 1994-1998
   • AUGMENTED (3X) FUNDING: $0.0 (STRATEGIC FUNDING: $14.0M)

5) ASIC DIGITAL SYSTEMS WITH SIGNAL PROCESSOR
   • CENTER: JPL
   • MISSIONS: EOS SAR, TOPSAT, RAIN RADAR
   • TIMEFRAME: 1993-1997
   • AUGMENTED (3X) FUNDING: $2.2 M (STRATEGIC FUNDING: $4.1M)

6) ANTENNA SURFACE DISTORTION COMPENSATION USING PIEZOELECTRIC ELEMENTS
   • CENTER: JPL
   • MISSIONS: TOPSAT, RAIN RADAR
   • TIMEFRAME: 1993-1997
   • AUGMENTED (3X) FUNDING: $0.0 (STRATEGIC FUNDING: $3.8M)

ACTIVE MICROWAVE SENSORS
FY93 3X PROGRAM
PRIORITIZATION (continued)

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

7) FLAT-PLATE MICROSTRIP REFLECT-ARRAY ANTENNA
   • CENTER: JPL
   • MISSIONS: EOS SCANSAT
   • TIMEFRAME: 1993-1997
   • AUGMENTED (3X) FUNDING: $0.0 (STRATEGIC FUNDING: $4.3M)

8) OPTICALLY CONTROLLED BEAMFORMING NETWORK
   • CENTERS: JPL, LaRC
   • MISSIONS: TOPSAT, RAIN RADAR
   • TIMEFRAME: 1993-1998
   • AUGMENTED (3X) FUNDING: $0.0 (STRATEGIC FUNDING: $5.1M)
### CENTER: JPL, LaRC, LeRC

**TITLE:** ACTIVE MICROWAVE SENSOR TECHNOLOGY (AUGMENTATION "3X" FUNDING)

<table>
<thead>
<tr>
<th>TOTAL &quot;3X&quot; FUNDING REQUIREMENT (CURRENT FUNDING IS $0)</th>
<th>FY93</th>
<th>FY94</th>
<th>FY95</th>
<th>FY96</th>
<th>FY97</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10 GHz MMIC ARRAYS</td>
<td>0.8</td>
<td>1.1</td>
<td>1.3</td>
<td>0.7</td>
<td>-</td>
<td>3.9</td>
</tr>
<tr>
<td>35 GHz COMPONENTS AND ARRAY</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
<td>2.7</td>
<td>3.0</td>
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<tr>
<td>CALIBRATION SUBSYSTEM</td>
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<td>0.6</td>
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<td>94 GHz COMPONENTS AND ARRAY</td>
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<td>0.0</td>
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<tr>
<td>ASIC DIGITAL SYSTEMS</td>
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<td>1.0</td>
<td>2.2</td>
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<tr>
<td>ANTENNA COMPENSATION</td>
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<td>-</td>
<td>-</td>
<td>0.0</td>
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<tr>
<td>FLAT PLATE REFLECT-ARRAY</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0</td>
</tr>
<tr>
<td>OPTICALLY CONTROLLED BFN</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>1.3</td>
<td>1.7</td>
<td>2.0</td>
<td>2.0</td>
<td>4.3</td>
<td>11.3</td>
</tr>
</tbody>
</table>

---

**ADVANCED RADAR TECHNOLOGY**

**TOPSAT SENSOR A/C PROTOTYPE DEVELOPMENT**

![Diagram](jpl.png)

- 35 GHz COMPONENTS
- T/R MODULE DESIGN
- ATTITUDE CONTROL AND LASER REF BASELINE DET SYSTEM
- ACTIVE ARRAY DEVELOPMENT TEST
- AIRBORNE TOPSAT PROTOTYPE
- MODIFICATIONS TO DC-8 SAR SYSTEM

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*SE6-14*
SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS
ACTIVE MICROWAVE SENSORS

TECHNOLOGY ROADMAP/SCHEDULE

<table>
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<tr>
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FOCUSED R&T
1-10 GHz MMIC Arrays
35 GHz Components and Array Development
Calibration Subsystems
ASIC Digital Systems
Antenna Compensation
Flat Plate Reflect-Array
Optically Controlled BFN

R&T BASE
Improve Performance
Devices 35-200 GHz

TOTAL FUNDING REQUIREMENT
FY93 FY94 FY95 FY96 FY97 TOTAL
1-10 GHz MMIC ARRAYS 0.8 1.3 1.0 0.8 - 3.9
35 GHz COMPONENTS AND ARRAY 2.0 3.0 3.0 2.6 1.7 12.3
CALIBRATION SUBSYSTEM 0.5 0.8 0.8 0.8 0.5 3.4
94 GHz COMPONENTS AND ARRAY 2.5 2.5 3.0 3.0 3.0 14.0
ASIC DIGITAL SYSTEMS 0.5 0.8 1.0 1.0 0.8 4.1
ANTENNA COMPENSATION 0.5 0.8 1.0 1.0 0.5 3.8
FLAT PLATE REFLECT-ARRAY 0.3 0.8 1.2 1.2 0.8 4.3
OPTICALLY CONTROLLED BFN 0.2 0.9 1.4 1.3 1.3 5.1
TOTAL 7.3 10.9 12.4 11.7 8.6 50.9

CENTER: JPL, LaRC, LeRC
TITLE: ACTIVE MICROWAVE SENSOR TECHNOLOGY (STRATEGIC FUNDING) ($K)

ACTIVE MICROWAVE SENSORS
STRATEGIC PROGRAM
RESOURCE SUMMARY

SE6-16
## Technology Program:
**Technology Area:** Science Sensors  
**Technology Element:** Active Microwave Sensors  
**Technology Sub-Element:** 1-10 GHz MMIC Arrays  
**Input Field Center:** JPL  
**Input Type:** Augmentation  
**Point of Contact:** John Curlander  
**Date:** June 26, 1991  
**LRP Thrust:** Science  
**LRP Specific Objective:** EOS Sensor Technology  
**Mission Applicability:** EOS SAR  

### Resource Requirements (FY in $M)

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<th>93</th>
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<td>0.8</td>
<td>1.1</td>
<td>1.3</td>
<td>0.7</td>
<td>0.0</td>
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</tr>
</tbody>
</table>

### Comments/Issues:
- Adaptive phase control implementation; controller interfaces; distributed control feasibility
- Array operating efficiency; tapered beam illumination performance; phase/amplitude errors
- Recommend funding be augmented to develop flight weight brassboard panel and control system

## Technology Program:
**Technology Area:** Science Sensors  
**Technology Element:** Active Microwave Sensors  
**Technology Sub-Element:** 35 GHz Components/Array  
**Input Field Center:** JPL, LeRC  
**Input Type:** Augmentation  
**Point of Contact:** John Curlander  
**Date:** June 26, 1991  
**LRP Thrust:** Science  
**LRP Specific Objective:** EOS Sensor Technology  
**Mission Applicability:** EOS SAR  

### Resource Requirements (FY in $M)

<table>
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<th>FY</th>
<th>93</th>
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<th>95</th>
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<tbody>
<tr>
<td>2.0</td>
<td>3.0</td>
<td>3.0</td>
<td>2.6</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>

### Comments/Issues:
- Array flatness, adaptive phase control implementation; controller interfaces; distributed control system operating efficiency; pointing determination accuracy; phase/amplitude errors
### Technology Program:

- **Technology Area:** Science Sensors
- **Technology Element:** Active Microwave Sensors
- **Technology Sub-Element:** Calibration Subsystems

### Input Information:
- **Input Field Center:** JPL
- **Input Type:** Augmentation
- **Point of Contact:** John Curlander

### Date:
- **June 26, 1991**

#### Technology Element Objectives/Description:

Develop systems for in-flight characterization of gain and phase performance vs. frequency for antenna at T/R module level and array level (requires <0.2 dB and <3 deg rms); develop systems for high precision pointing determination of antenna electronics boresight (requires <0.0003 deg over time intervals of 100ms).

### Task Schedule/Milestones:

- **FY93:** Requirements study; performance analysis for active array calibration subsystem
- **FY94:** Subsystem design for distributed array calibration system
- **FY95:** Breadboard prototype; high precision beam pointing subsystem technology survey
- **FY96:** Test of array calibration subsystem in airborne radar; precision pointing subsystem test article
- **FY97:** Breadboard prototype of precision pointing subsystem

#### Comments/Issues:

- Calibration performance is limiting factor in SAR science; SIR-c not calibrated;
- Topographic mapper pointing accuracy requirement is order of magnitude greater than TOPEX

---

### Resource Requirements:

<table>
<thead>
<tr>
<th>FY</th>
<th>93</th>
<th>94</th>
<th>95</th>
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<tbody>
<tr>
<td>$M</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
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### Technology Program:

- **Technology Area:** Science Sensors
- **Technology Element:** Active Microwave Sensors
- **Technology Sub-Element:** ASIC Digital Subsystems

### Input Information:
- **Input Field Center:** JPL
- **Input Type:** Augmentation
- **Point of Contact:** John Curlander

### Date:
- **June 26, 1991**

#### Technology Element Objectives/Description:

Develop customized integrated circuits for radar sensor digital signal processing applications; digital controllers, data formatting functions and signal processing for pulse compression on an IC chip set; requires dual ADCs operating at 200 MHz with 8bps, large, fast RAM (>64 MB), and high speed signal processing (>1GFLOP).

### Task Schedule/Milestones:

- **FY93:** Requirements study; performance analysis
- **FY94:** Subsystem design for integrated digital processor
- **FY95:** Chip procurement, laboratory test and evaluation
- **FY96:** Breadboard prototype (partial completion)
- **FY97:** Breadboard prototype, completion test with airborne radar system

#### Comments/Issues:

- Radar digital subsystems for multi-frequency, multi-polarization SAR is large fraction (> 50%) of instrument volume and mass; and significant fraction of power consumption (>15%)
- Downlink data rate can be substantially reduced with on-board signal processing and multi-look filtering; large cost savings in ground data handling, more efficient data distribution.
INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

SENSOR ELECTRONICS
PROJECT SUMMARY

SCIENCE SENSING PROGRAM AREA
OF THE
SPACE SCIENCE TECHNOLOGY PROGRAM

June 27, 1991

Office of Aeronautics, Exploration and Technology
National Aeronautics And Space Administration
Washington, D.C. 20546

DRAFT 6/1991  Page 1

HYBRID FOCAL-PLANE ARRAYS
IMPORTANCE OF LOW READOUT NOISE

Signal/Noise

Telescope Aperture and Optics
- Big $ every time
- Quantum efficiency
  - See detector program

Photon Shot Noise
- Fundamental
  - Readout Electronics
- Wide applicability, less $ 

PROGRAM DRIVERS

- In almost all low background scientific imaging systems, system detectivity is limited by readout electronic noise.
- Readout electronics typically dominate focal-plane power dissipation.
- High-throughput systems are often bottle-necked by the readout electronics.
- Noise in state-of-the-art readout electronics devices becomes unacceptable at cryogenic temperatures (e.g. 10K).
- Readout electronics, such as CCDs, are highly susceptible to radiation damage and other effects when used in harsh environments.
- The integration of performance-enhancing readout electronics is hampered by a lack of available circuit technologies.

SPACE SCIENCE TECHNOLOGY SCIENCE SENSING SENSOR ELECTRONICS

TECHNOLOGY NEEDS

- SENSOR ELECTRONICS ADDRESSES THE NEEDS FOR DETECTOR READOUT AND PACKAGING INCLUDING AMPLIFIERS, MULTIPLIERS, BACKPLANE PROCESSING, AND DATA CONVERSION.

- CURRENT TECHNOLOGY CANNOT MEET REQUIREMENTS FOR FUTURE MISSIONS IN THE UV, VIS, IR, X-RAY, AND 1-METER REGIONS. NEED: SMART LDR, APD, TT&EE, GASBO, TUBE AXE, SET, PIN, VGA, 3D, SAGE, LITE & SAGE, SIRL, ESTAR, NSR, S2R & E, WHICH INCLUDE:
  - CRYOGENIC OPERATION
  - SMART ELECTRONICS
  - HIGH THROUGHPUT
  - LOW POWER CONSUMPTION

SPACE SCIENCE TECHNOLOGY SCIENCE SENSING SENSOR ELECTRONICS

TECHNOLOGY CHALLENGES/APPRAOCH

- CRYOGENIC READOUT ELECTRONICS OPERATING IN THE 3-4K RANGE
  - 2 DEG P英才, 5 GASBO, 5 TE2B, SUPERCONDUCTORS

- SMART ELECTRONICS READ NOISE IN 1-10 AND 1-10H ARRAY NITS
  - HIGH WORK FUNCTION AMPLIFIER
  - ADVANCED CMOS CIRCUITS

- INCREASED ELECTRONICS INTEGRATION WITH REDUCED HEAT LOAD AND LOWER NOISE
  - 3D MICRO-ELECTRONICS (3D-PLANE, 4D)
  - ADVANCED INTERFACES OPTICAL LINKS
  - LARGE FORMAT ARRAYS/ARRAYS

- INCREASED SENSOR SYSTEM THROUGHPUT
  - ADVANCED ARCHITECTURE FOR SMART READOUT
  - LOW POWER VERS.

SE7-2
STATE OF THE ART ASSESSMENT

- CRYOGENIC READOUT ELECTRONICS
  - NOISE ACCEPTABLE BELOW 1 nV
  - NOISE AT 5-K 9 EXCESSIVE

- READ NOISE
  - 5 VGS RMS IN CCD
  - APPROX 25 LS RMS IN A SWITCHED ARRAY BUSA

- DETECTOR AND ELECTRONICS INTEGRATION
  - 400 x 400 MCC CCD ARRAYS
  - 50 x 50 MCC INTEGRATED
  - INTEGRATED CRYOGENIC READOUT ELECTRICALS

SENSOR SYSTEM THROUGHPUT
- CCD READOUT RATE 500 kHz

CURRENT PROGRAM
NONE

3X AUGMENTED PROGRAM
1) Low-noise cryogenic readout electronics
   - Expand current cryostat electronics to cryogenic operation. All
     achievable technologies have been demonstrated at 2 K. Significant
     noise reduction in readout devices operating in the 50-80 K range.
     Approach includes: probes, £000, LT5.

2) Devices and circuits for sub-electron read noise
   - Readout read noise in CCD output increased from 1 nV to sub-electron levels
   - Readout read noise in 10K with readout up to 50 nV to 1 nV or 0

3) Advanced packaging and interfaces
   - Develop advanced packaging and interface techniques to enhance sensor system
     performance. Develop comprehensive and testing for large format CCD and 10 line-array
     arrays. Emphasize advanced techniques for reducing noise from read and noise.
     Emphasize 3-D integration in increased readout circuits. Emphasize advanced detector systems

4) Advanced readout architectures
   - Develop advanced readout architecture to enhance sensor system throughput
     and reduce power dissipation. Use new design strategies for low-noise operation and energy
     rejection. Microminiature readout systems BSS-10, VLSI design for multi-sensor arrays and
     pattern recognition.

5) Low-power, high-speed integrated circuits
   - Reduce power dissipation by twenty-five and monolithic sensor readout electronics to
     allow operation on sealed radiation environment and reduce data transmission rates from the
     spacecraft while preserving essential scientific data return. Approach includes: probes, £000, LT5
     and 5-10 C MOS

TECHNOLOGY PERFORMANCE OBJECTIVES

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<th>TYPICAL REQUIREMENT</th>
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*ORIGINAL PAGE IS OF POOR QUALITY*
SENSOR ELECTRONICS

TECHNOLOGY ROADMAP SCHEDULE

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SPACc SCIENCE TECHNOLOGY SCIENCE SENSING
SENSOR ELECTRONICS

OTHER DEVELOPMENT EFFORTS

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<td>LOW-Power, VERY HIGH SPEED INTEGRATED CIRCUITS</td>
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PRELIMINARY FY93 FY AUGMENTATION

1) Low-noise cryogenic readout electronics
2) Devices and circuits for sub-electron read noise
3) Advanced packaging and interfaces
4) Advanced readout architectures to increase sensor system throughput
5) Low-power, very high speed integrated circuits for microwave radiometer backends

OBJECTIVES

- Programmatic
  - Improve sensor system performance using advanced sensor readout electronics and packaging technology
- Technical
  - Cryogenic readout electronics
  - Sub-electron read noise
  - Advanced packaging and interfaces
  - Low power

RESOURCES

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PARTICIPANTS

- JPL
- SEC
- LMS
- USA
- NASA
IPLC! SC_
TI CNNC_.OGV
SQ lh Ci ._
NS lg V
SENSOR ELECTRONICS
BREAKDOWN (3 OF 3)
LOW POWER VHSC

OBJECTIVES
- Programmatic
- 1993: Low power VHSC technology development
- 1994: Development of S-6” S-CMOS
- 1995: Development of S-6” S-CMOS
- 1996: Breakdown of S-6” S-CMOS
- 1997: Technology development and technology validation

RESOURCES
- 1993: 16K
- 1994: 15K
- 1995: 10K
- 1996: 10K
- 1997: 10K

PARTICIPANTS
JPL

2X AUGMENTATION FUNDING
No on-going work

SUB-ELEMENT
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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING
SENSOR ELECTRONICS
FY 93 ALLOCATION OF 2X FUNDING
Cryogenic Helio-electronics
- 6.00 ATC S-CMOS
- 6.50 JPL design, development, and operation of S-6” S-CMOS
- 0.10 Contract for development of S-6” S-CMOS
- 0.30 Infrastructure costs

Advanced Packaging & Interfaces
- 0.05 ATC S-CMOS
- 0.10 JPL design, development, and operation of S-6” S-CMOS
- 0.30 Contract for development of S-6” S-CMOS

Advanced Helio-electronics
- 0.05 ATC S-CMOS
- 0.10 JPL design, development, and operation of S-6” S-CMOS
- 0.30 Contract for development of S-6” S-CMOS

Low Power VHSC
- 0.05 ATC S-CMOS
- 0.10 JPL design, development, and operation of S-6” S-CMOS

JPL

Mission Set

SE7-6
### OPTICS TECHNOLOGY BASE R&T PROGRAM

**OAET, OSSA AND SCIENCE COMMUNITY INPUTS TO PROGRAM PLAN**

- Industry Tours, February-April 1991
- Large Filled Aperture Telescopes in Space Workshop, March 4-5, 1991
- ASTROTECH 21 Optics Technology Workshop, March 6-8, 1991
- The Decade of Discovery in Astronomy and Astrophysics (Bahcall Report), March 18, 1991
- Exploration Technology Planning Update, March 19, 1991
- OSSA Division Technology Needs (Draft), April 12, 1991
- Technologies for Advanced Planetary Instruments Workshop, May 8-10, 1991

---

**INTEGRATED SPACE TECHNOLOGY PLAN**

**SCIENCE**

**SCIENCE TECHNOLOGY MISSION MODEL**

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<td>THEMIS Charlie Satellite</td>
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<td>THEMIS Tau Satellite</td>
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<td>THEMIS (ZZ)</td>
<td>THEMIS Zeta Satellite</td>
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**IMAGE CONTENT**

The image contains a table and a diagram related to integrated space technology plans, science, and mission models. The table lists various projects and their associated years and descriptions. The diagram illustrates the integration of various satellite observatories and exploratory missions, highlighting their roles in different scientific domains such as astrophysics, solar system exploration, Earth science, space physics, communications, life science, and microgravity.
OPTICS TECHNOLOGY BASE R&T PROGRAM
RELATIONSHIPS BETWEEN OAET PROGRAMS

FOCUSED R&T

- MICRO-PRECISION CSI
- TELESCOPE OPTICAL SYSTEMS
- PRECISION INSTRUMENT POINTING
- SENSOR OPTICS TECHNOLOGY

BASE R&T

- MATERIALS & STRUCTURES TECHNOLOGY
- OPTICS TECHNOLOGY
- CONTROL TECHNOLOGY
- SENSORS TECHNOLOGY

Focused Technology Programs
Development and Demonstration
Higher Levels of Maturity
Mission Pull
Technology Research Foundation
Lower Levels of Maturity
Technology Push

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS
SENSOR OPTICAL SYSTEMS

WHERE IS IT?

SCENE PHOTONS → TELESCOPE OPTICS → SENSOR OPTICS (PHOTON FORMATOR) → DETECTORS → DATA FLOW
DEFINTION

Optical components between the telescope optics and focal plane detectors

- Process incoming time-dependent photon stream
- Format photons according to science requirements
  -- Scene spatial distribution
  -- Spectral passband
  -- Temporal binning
  -- Polarization
- Format images to accommodate sensor architecture

CHARACTERISTICS

- Smaller than telescope optics
- Sophisticated functions requiring highest quality optics
- Novel fabrication methodologies

Criticality of SENSOR OPTICS

Example: Hubble Space Telescope

Wide Field and Planetary Camera (WF/PC)
  - Re-format image to accommodate sensor architecture
  - Spectral signatures
  - Polarization
  - The new WF/PC will correct the HST wavefront aberration

SENSOR OPTICAL SYSTEMS technology is being applied to the new WF/PC
OPTICS TECHNOLOGY
PROGRAM STRUCTURE

OPTICS TECHNOLOGY

OPTICS MODELLING
- SCATTERING
- DIFFRACTION ANALYSIS
- STRAY LIGHT
- THERMOOPTICAL PROPERTIES
- OPTIMIZATION
- INTEGRATED MODELLING

OPTICAL MATERIALS & COATINGS
- HIGH PRECISION SUBSTRATES
- DIMENSIONALLY STABLE LOW MASS MATERIALS
- CRYOGENIC MATERIALS
- DIFRACTIVE MATERIALS
- LOW DIFFRACTION MASKS AND STOPS
- LOW SCATTER COATINGS
- TAILORED OPTICAL COATINGS

OPTICS FABRICATION
- ADVANCED REPLICATION
- POLISHING SCIENCE
- TRUE FIGURING
- ION MILLING AND ION ASSISTED ETCHING
- CRYO NULL FIGURING
- LARGE AREA THIN FILM & COATINGS
- INTEGRATED OPTICAL ASSEMBLIES
- GRAZING INCIDENCE OPTICS

OPTICS TEST
- SURFACE FIGURE & ROUGHNESS
- IMAGE QUALITY
- STRAY LIGHT
- ASPHERIC FIGURE MEASUREMENT
- NARROW ANGLE TESTING
- CRYOGENIC OPTICS TESTING
- INTEGRATED FABRICATION TESTING

WAVEFRONT SENSING AND CONTROL
- WAVEFRONT SENSORS
- ACTIVE OPTICS
- LASER METROLOGY
- SYSTEM CONTROL ARCHITECTURE
- NONLINEAR OPTICS
- INTERFEROMETRY

SENSOR OPTICS
- ADVANCED GRATINGS
- TUNABLE FILTERS
- OPTICAL COMPONENTS
- HIGH DYNAMIC RANGE IMAGING
- NONLINEAR OPTICS
- CORRELATORS

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS
SENSOR OPTICAL SYSTEMS

TECHNOLOGY ASSESSMENT AND CHALLENGES

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<tr>
<th>Need</th>
<th>Assessment</th>
<th>Challenge</th>
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<tr>
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<tr>
<td>Small cameras for Orbiters/Rovers</td>
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<td>0.1 m³</td>
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<td>10⁻¹⁰</td>
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<td>Integrated Optics Imaging Spectrometer</td>
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<td>design, fabricate, test</td>
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TECHNOLOGY EFFORT PROGRAM GOALS

- Provide the enabling SENSOR OPTICS technologies for advanced NASA space science missions
- Advance maturity of SENSOR OPTICS technology to a level of readiness appropriate for mission baseline design
- Develop high fidelity test beds as an alternative to complex technology flight experiments
- Strengthen NASA partnerships with industry and academia

PROGRAM BENEFITS

- Create new technological capabilities to enable and expand options for NASA missions
- Improve understanding of cost, schedule and performance trade-offs for future NASA space science missions through in-house participation in optics technology development
- Greater NASA capability in optics technology
  - Needed now to work with external community to develop meaningful space missions
  - Needed later to support projects
- Optical Sciences Educational Opportunities
CONCLUSIONS

- Requirements levied on NASA SENSOR OPTICS are unique
- Next generation science measurement objectives require more sophisticated SENSOR OPTICS which need optics technologies not yet developed
- Theory, computational analysis and hardware technology demonstration are needed
- Industrial and academic partnership needed
- NASA mission success depends greatly on "in-house" expertise

RECOMMENDATIONS

- NASA Invest $5 - 8M/yr in SENSOR OPTICS R&D
- Form an optics technology working group to:
  - Coordinate efforts between OAET programs
  - Develop additional programs that cover related optics areas (photonics, etc.)
- Increase NASA emphasis on optical sciences educational opportunities
THE COOLERS AND CRYOGENICS TECHNOLOGY PROGRAM WILL SUPPORT THE FULL RANGE OF SPACE SCIENCE INSTRUMENT COOLING AND CRYOGENIC TECHNOLOGY NEEDS, INCLUDING:

- EARTH OBSERVING SYSTEM INFRARED INSTRUMENTS REQUIRE LOW VIBRATION 30 TO 65 K COOLERS
  - EOS AND GEOPLATFORM INSTRUMENTS

- HUBBLE SPACE TELESCOPE (HST) REPLACEMENT INSTRUMENTS AND HST FOLLOW-ON REQUIRE 10 TO 80 K VIBRATION-FREE COOLERS
  - HST, LTT, NGST, ST-NG, IMAGING INTERFEROMETER

- SUBMILLIMETER, LWIR AND X-RAY ASTROPHYSICS MISSIONS REQUIRE LONG-LIFE 2-5 K LOW-VIBRATION COOLERS
  - SMMM, LDR, SMILS, SMMI, AXAF
TECHNOLOGY CHALLENGES/APPROACH

• TECHNOLOGY DEVELOPMENT CHALLENGES:
  - EXTEND MISSION LIFE AND INCREASE SCIENCE DATA RETURNED
  - SPECIFIC CHALLENGES INCLUDE:
    - EXTEND LIFETIME WITH HIGH RELIABILITY
    - MINIMIZE VIBRATION AND INSURE INTEGRATION WITH INSTRUMENTS/SPACECRAFT
    - INCREASE COOLER EFFICIENCY AND REDUCE THERMAL LEAKAGE
    - INSURE ADEQUATE END-OF-LIFE PERFORMANCE
    - DEMONSTRATE HIGH EFFICIENCY COOLER FOR 2-5 KELVIN

• TECHNOLOGY DEVELOPMENT APPROACH
  - BASE RESEARCH ON RAPIDLY DEVELOPING CRYOGENIC COOLER TECHNOLOGY
    - INCLUDING NEW VIBRATION-FREE CONCEPTS, LONG-LIFE 2-5 K COOLER FEASIBILITY
      DEMONSTRATIONS AND SUBKELVIN REFRIGERATORS
  - FOCUSED DEVELOPMENT OF BRASSBOARD COOLERS
    - PLANNED AGAINST PROJECTED MISSION NEED DATES
  - COORDINATE PLANNING AND IMPLEMENTATION WITH OSSA COOLER ADVANCED
    DEVELOPMENT
  - FLIGHT EXPERIMENTS OF PROTOTYPE COOLERS

STATE OF THE ART ASSESSMENT

• LONG-LIFE, LOW-VIBRATION 30-80 K COOLERS
  - 55 - 80 K OXFORD-HERITAGE STIRLING COOLERS UNDER DEVELOPMENT FOR EOS-A
  - 30 K STIRLING COOLERS UNDER DEVELOPMENT FOR EOS-B
  - NEW VIBRATION REDUCTION TECHNOLOGIES UNDER DEVELOPMENT

• LONG-LIFE 2 - 5 K COOLING
  - STORED LIQUID HELIUM
    - LIMITED LIFE - 1 YR
    - LIMITED INSTRUMENT COOLING - 30 mW
  - CLOSED CYCLE COOLERS
    - SEVERAL FEASIBLE CONCEPTS BEING INVESTIGATED
      - IMMATURE TECHNOLOGY

• VIBRATION-FREE LONG-LIFE COOLING FOR 10 TO 80 K
  - FEASIBILITY DEMONSTRATED USING SORPTION J-T AND TURBO-BRAYTON
    - CRITICAL COMPONENT TESTING UNDERWAY

• SUB-KELVIN COOLERS
  - 3 HE COOLER FLOWN ON SOUNDING ROCKET - 0.3 K
  - ADR AND DILUATION COOLERS BEING DEVELOPED - 50-100 mK
CURRENT PROGRAM

• DEVELOP AND DEMONSTRATE A LONG LIFETIME 30 K STIRLING CYCLE COOLER (GSFC)
  • FOCUSED PROGRAM TO PROVIDE 30 K COOLER FOR EOS-B INSTRUMENTS
  • BRASSBOARD COOLER WILL DEMONSTRATE 5 YEAR LIFETIME, LOW VIBRATION (LESS
  THAN 0.05 POUND FORCE), 300 MW OF COOLING POWER AT 30 K, HIGH EFFICIENCY
  (LESS THAN 75 WATT INPUT POWER) AND EASE OF INTEGRATION

• FLIGHT OF A 65 K STIRLING COOLER (JPL)
  • DEMONSTRATE LOW VIBRATION OPERATION IN SPACE
  • DEMONSTRATE SOLUTIONS FOR COOLER TO INSTRUMENT INTERFACE ISSUES

• MAINTAIN LOW LEVEL OF R&D ON ADVANCED COOLER CONCEPTS
  • DEVELOP COOLER TECHNOLOGY TO PROVIDE IMPROVED NEXT GENERATION COOLERS
  • DEVELOP SUB-KELVIN REFRIGERATION

AUGMENTED PROGRAM

• LONG LIFETIME VIBRATION FREE COOLER DEVELOPMENT
  • 65 K SORPTION AND BRAYTON
  • 10-30 K SORPTION AND BRAYTON

• 2-5 K LONG-LIFE MECHANICAL REFRIGERATION DEVELOPMENT

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<th>ATTRIBUTES</th>
<th>CANDIDATE TECHNOLOGIES</th>
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<td>10-20 MW AT 2 K</td>
<td>TURBO BRAYTON</td>
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<tr>
<td>50-100 MW AT 4-5 K</td>
<td>J-T + UPPER STAGES</td>
</tr>
<tr>
<td>LOW VIBRATION</td>
<td>4K STIRLING + UPPER STAGES</td>
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<tr>
<td>LESS THAN 1 KW INPUT POWER</td>
<td>MAGNETIC + UPPER STAGES</td>
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• DEMONSTRATE PROMISING ADVANCED COOLER TECHNOLOGIES
  • PARASITIC REDUCTION FOR SUPERFLUID HELIUM DEWAR
  • ADVANCED SUBKELVIN COOLER CONCEPTS
  • PULSE TUBE AND ADVANCED PASSIVE COOLER TECHNOLOGIES
  • FUNDAMENTAL COOLER PHYSICS RESEARCH
### 2.5 K Cooler

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<tr>
<th>Mission Requirement</th>
<th>Current SOA*</th>
<th>Cooler for SMMM, LDR</th>
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<td>Temperature</td>
<td>1.5 - 2 K</td>
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<td>4 - 5 K</td>
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<tr>
<td>Cooling Power</td>
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<td>10 - 20 mW</td>
<td>50 - 100 mW</td>
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<tr>
<td>Input Power</td>
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<td>&lt; 1 KW</td>
<td>&lt; 1 KW</td>
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<tr>
<td>Cooler Mass</td>
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<td>&lt; 50 KG</td>
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<td>Vibration</td>
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<td>&lt; 0.05 LBF</td>
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<tr>
<td>Lifetime</td>
<td>&lt; 1 YR</td>
<td>&gt; 10 YR</td>
<td>&gt; 10 YR</td>
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<td>Need Date</td>
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*STORED LIQUID HELIUM

### Vibration-Free Coolers

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<td>2 - 80 K</td>
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<td>Cooling Power</td>
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<td>Input Power</td>
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<td>Cooler Mass</td>
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<td>20 KG</td>
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<tr>
<td>Vibration</td>
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<td>- 0</td>
<td>- 0</td>
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<tr>
<td>Lifetime</td>
<td>&lt; 1 YR</td>
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<td>Need Date</td>
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*STORED CRYOGEN COOLERS
SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS AND CRYOGENICS

TECHNOLOGY ROADMAP/SCHEDULE

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<td>PROGRAM OFFICE</td>
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<td>OTHER DEVELOPMENT EFFORTS</td>
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- GSFC EOS PROJECT COOLER QUALIFICATION PROGRAM
  - TWO PARALLEL INDUSTRY CONTRACTS
    - GOAL: 80 K GENERAL EOS-A COOLER
    - FLIGHT COOLER AVAILABILITY: 1994 (PROJECTED)

- JPL/LORAL FUNDED BY OSSA FOR AIRS INSTRUMENT (EOS-A) COOLER ADVANCED DEVELOPMENT
  - TWO PARALLEL INDUSTRY CONTRACTS
    - GOAL: 55 K COOLER FOR AIRS
    - FLIGHT COOLER AVAILABILITY: 1994 (PROJECTED)

- STRATEGIC DEFENSE INITIATIVE OFFICE/U.S. AIR FORCE COOLER PROGRAM UNDERWAY
  - TWO PARALLEL INDUSTRY CONTRACTS
    - GOAL: 2W, 65 K STANDARD SPACECRAFT COOLER
    - FLIGHT COOLER AVAILABILITY: TBD

- TWO NASA SBIR PROGRAMS FOR 2-5 K LOWER STAGE COOLER DEMONSTRATIONS ARE ONGOING

SE9-5
SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS & CRYOGENICS

FY93 AUGMENTATION
PRIORITIZATION:
Focused Program

- Long life 2-5 K mechanical cooler
- Vibration free 20-30 K sorption cooler
- Vibration free 65 K Brayton cooler
- Vibration free 2 K magnetic cooler, lower stage
- Vibration free 2 K cooler, upper stage
- Vibration free 65-80 K sorption cooler

COOLER FLIGHT EXPERIMENTS

CRITICAL MILESTONES

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<th>93</th>
<th>94</th>
<th>95</th>
<th>96</th>
<th>97</th>
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<th>03</th>
<th>04</th>
<th>05</th>
<th>06</th>
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<td>55-80 K Stirling (In-Step)</td>
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<td>3 He (Unfunded)</td>
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<td>Subkelvin Coolers</td>
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<td>30 K Stirling</td>
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<td>2.5 K long-life mechanical</td>
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## SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

### COOLERS & CRYOGENICS

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<th>SUB-ELEMENTS</th>
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<th>96</th>
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<td>30 K STIRLING</td>
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High-Temperature Superconductivity
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM
ITP EXTERNAL REVIEW

BRIEFING ON THE
NASA
HIGH TEMPERATURE SUPERCONDUCTIVITY
PROGRAM

JUNE 27, 1991
EDWIN G. WINTUCKY

OFFICE OF AERONAUTICS, EXPLORATION AND TECHNOLOGY

HIGH TEMPERATURE SUPERCONDUCTIVITY

OUTLINE

- OBJECTIVE AND RATIONALE
- SSTAC AD HOC REVIEW TEAM FINDINGS
- SPACE APPLICATIONS AND BENEFITS
- APPROACH
- PROGRAM ORGANIZATION AND CONTENT
- ACCOMPLISHMENTS
- FUNDING
- FACILITIES
- HTS AUGMENTATION
- RELATED NON-NASA HTS EFFORTS
- ISSUES
HIGH TEMPERATURE SUPERCONDUCTIVITY

OBJECTIVE
TO INVESTIGATE THE POTENTIAL OF HTS TECHNOLOGY TO ENHANCE/ENABLE NASA MISSIONS AND TO DEVELOP AND DEMONSTRATE HTS DEVICES FOR IDENTIFIED MISSIONS

RATIONALE
HIGH TEMPERATURE SUPERCONDUCTIVITY IS A REVOLUTIONARY TECHNOLOGY OF GREAT POTENTIAL TO LEO, GEO, LUNAR AND PLANETARY MISSIONS

- A WIDE VARIETY OF SPACE APPLICATIONS HAVE BEEN IDENTIFIED IN THE AREAS OF COMMUNICATIONS AND DATA SYSTEMS, SENSORS AND CRYOGENIC SYSTEMS, AND POWER AND PROPULSION SYSTEMS

- UNIQUE ELECTRICAL, MAGNETIC AND THERMAL PROPERTIES OFFER POSSIBLE MAJOR IMPROVEMENTS IN SYSTEM PERFORMANCE AND RELIABILITY, LARGE REDUCTIONS IN SIZE, WEIGHT AND ELECTRICAL POWER REQUIREMENTS, AND EXTENSION OF MISSION LIFE

- RECENT RAPID IMPROVEMENTS IN HTS THIN FILM AND BULK MATERIALS, EVIDENCE OF PAYOFFS AT SYSTEM LEVEL, SYSTEM STUDIES AND FUTURE MISSIONS TECHNOLOGY REQUIREMENTS JUSTIFY DEVICE DEVELOPMENT AND DEMONSTRATION

SSTAC/HTS AD HOC REVIEW TEAM FINDINGS

"In general, we support the proposed NASA program. Superconductivity presents significant promise for space applications. Whether this promise is realized depends upon future developments in materials technology and implementation of space hardware. NASA should continue to closely monitor the progress of superconductivity developments while actively exploring promising space applications. If superconductivity materials technology yields productive devices, then NASA should be positioned to capitalize with new missions exploiting the new technology."

Committee Chairman Steven D. Dorfman in a letter prefacing the final report of the Ad Hoc Review Team for the NASA High Temperature Superconductivity Program, dated 20 July 1988, to Norm Augustine, then Chairman of SSTAC.
TWO RECOMMENDATIONS OF THE HTS AD HOC REVIEW TEAM:

- NASA should focus on applications and associated research peculiar to NASA's space and aeronautical missions and rely to a large extent on fundamental research on materials or theoretical research funded elsewhere.

- A long list of potential space applications have been identified. The next step is to do sufficient studies, including critical exploratory experiments, to identify the most promising applications for further development. This study and exploratory experimental effort should be the focus of the FY1988 and FY1989 program activities. The committee recommends that NASA propose a funding wedge beginning in FY1990 at $10-20 million. This is based upon the assumption that continued advances in materials will be made and that viable applications will be identified by that time to warrant continued research and technology development.

SPACE APPLICATIONS OF HIGH TEMPERATURE SUPERCONDUCTIVITY

PASSIVE & ACTIVE
MICROWAVE/MM WAVE COMPONENTS:
FILTERS,
RESONATORS
HI Q CAVITIES
TRANSMISSION LINES

SUBSYSTEMS:
LOW NOISE AMPLIFIERS & RECEIVERS
PHASED ARRAY ANTENNAS
DIGITAL SIGNAL PROCESSING

IR DETECTORS
SIS & SNS MIXERS
SNS SQUIDS THz LOCAL OSCILLATORS
FPA VIBRATION DAMPING
FPA GROUNDING STRAP
CURRENT LEADS
PASSIVE MAGNETIC BEARINGS

POWER AND PROPULSION

POWER TRANSMISSION LINES
ENERGY STORAGE:
MOMENTUM WHEELS
SMES
ACTIVE BEARINGS FOR HYDROGEN ROCKET ENGINE TURBO PUMPS
HIGH TEMPERATURE SUPERCONDUCTIVITY

POTENTIAL PAYOFFS

- LOW LOSS, HIGHER SENSITIVITY MICROWAVE CIRCUITS
- REDUCED SIZE AND WEIGHT OF MICROWAVE COMPONENTS/SUBSYSTEMS
- ENABLE MECHANICAL CRYOCOOLER VIBRATION DAMPING BY UP TO TWO ORDERS OF MAGNITUDE
- EXTEND MISSION LIFE OF STORED LIQUID HELIUM CRYOGENS BY 25% OR MORE
- ENABLE PASSIVELY COOLED IR BOLOMETERS FOR LONG LIFE SPACE SCIENCE MISSIONS
- GREATER RELIABILITY, LIFE TIME AND EFFICIENCY OF CRYOCOOLERS

APPROACH

- CONDUCT STUDIES TO IDENTIFY APPLICATIONS, EVALUATE BENEFITS AND DEFINE SYSTEM INSERTION REQUIREMENTS
- CONDUCT RESEARCH EFFORTS TO IDENTIFY/DEVELOP INNOVATIVE CONCEPTS FOR FUTURE APPLICATIONS
- DEVELOP, BUILD AND TEST DEVICES FOR SPACE APPLICATIONS DEEMED MOST PROMISING FOR NEAR TERM SYSTEM INSERTION AND MISSION ENHANCEMENT
- INVESTIGATE IDENTIFIED HIGH-PAYOFF, HIGH-RISK APPLICATIONS
- PARTICIPATE IN FLIGHT OPPORTUNITIES TO DEMONSTRATE FLIGHT QUALIFICATION AND FUNCTIONALITY IN SPACE
- LEVERAGE OFF DoD EXPERTISE AND INVESTMENT BY PURSUING COLLABORATIVE EFFORTS IN AREAS OF MUTUAL INTEREST AND BENEFIT
- BALANCE PROGRAM BETWEEN IN-HOUSE, UNIVERSITY AND INDUSTRY RESOURCES
- SUPPORT TRANSITION TO FOCUSED PROGRAMS AND NASA USERS
HIGH TEMPERATURE SUPERCONDUCTIVITY

HTS PROGRAM ORGANIZATION

MICROWAVE & mm WAVE COMMUNICATIONS
- PASSIVE COMPONENTS
  FILTERS, RESONATORS, HIQ CAVITIES, TRANSMISSION LINES
- HYBRID HTS/SEMICONDUCTOR CIRCUITS
- ACTIVE COMPONENTS
  LOW NOISE AMPLIFIER, OSCILLATOR, PHASE SHIFTER
- SUBSYSTEMS
  LOW NOISE RECEIVER, PHASED ARRAY ANTENNA, DIGITAL SIGNAL PROCESSOR

SENSORS
- IR DETECTORS
- SNS MICROBRIDGES
  TL LOCAL OSCILLATOR, SQUIDS, MIXER FOR SUBmm WAVE, ASTRONOMY
- SIS MIXER
- HYBRID HTS/SEMICONDUCTOR CIRCUITS
- RADIOMETRY

CRYOGENIC SYSTEMS
- VIBRATION DAMPING OF FPA
- FPA GROUNDING STRAP
- CURRENT LEADS FOR THERMAL ISOLATION
- PASSIVE MAGNETIC BEARINGS FOR BRAYTON CYCLE CRYOCOOLER
- FLUX PUMP REFRIGERATOR

CURRENT HTS PROGRAM - COMMUNICATIONS

OBJECTIVE: To develop and demonstrate the applicability of HTS to microwave and mm wave communications

APPROACH:
- Develop sources of films on microwave substrates (in-house, grant, contract)
- Develop hybrid HTS/semiconductor circuits
- Design, fabricate and test selected HTS circuits (passive & active components, subsystems)
- Perform system studies to identify and define promising applications

APPLICATIONS:
- Deep space communications - ground stations and data relay satellites
- Intersatellite communications links
- Commercial communications satellites

BENEFITS:
- Low insertion loss enables miniaturization
- Low loss beam forming networks enable high gain phased array antennas
- Low noise receivers significantly reduce power required for spaceborne transmitters

RELATED TECHNOLOGY:
- Long life, reliable miniature cryocoolers

STATE OF THE ART:
- Films of YBCO & TBCO with good Tc, Jc, Rs properties commercially available
- Passive components-excellent performance demonstrated-low insertion loss, high Q, high out-of-band rejection relative to metals

CHALLENGES:
- High quality & uniform films over large area (5 cm dia) on suitable substrates
- HTS/semiconductor integrated circuit fabrication
- Demonstration of performance at subsystem level

ACCOMPLISHMENTS:
- A number of technology "firsts"
- Reproducible deposition of high quality films
- Fabrication of passive circuits, including filters, resonators, phase shifters, antennas
- Delivery of HTSSE I experiments

FUTURE PLANS UNDER PRESENT FUNDING:
- HTSSE II experiment
- Development of monolithic HTS/semiconductor circuits

PROGRAM RESOURCES (WITH $0.5M REPROGRAMMED ANNUALLY AT LDRS) INSUFFICIENT FOR SUBSYSTEM DEVELOPMENT AFTER HTSSE II

SU1-5
COMMUNICATIONS APPLICATIONS STUDY

- Ku-BAND AND Ka-BAND GROUND TERMINAL LOW NOISE RECEIVERS
  - IMPROVE RECEIVER SENSITIVITY USING CRYO COOLED HTS/SEMICONDUCTOR CIRCUITRY
  - FACTOR OF 3 REDUCTION OF SPACECRAFT TRANSMITTER POWER
- ULTRA LOW NOISE SPACECRAFT RECEIVERS AT 7, 30, 60 AND 94 GHz
  - HTS RECEIVERS ON DEEP SPACE RELAY SATELLITE MAKES FEASIBLE mm-WAVE COMMUNICATIONS THROUGH SIGNIFICANT REDUCTION OF TRANSMITTER POWER AND INCREASE IN LINK DATA RATES
- PHASED ARRAY RECEIVER ANTENNA AT 14, 20, 30 AND 60 GHz
  - SIGNIFICANTLY REDUCED INSERTION LOSS IN BEAM FORMING NETWORK ENABLES LARGE (HIGH DIRECTIVITY) ARRAYS FOR DEEP SPACE AND SATELLITE COMMUNICATIONS
- 60 GHz LOW POWER, HIGH DATA RATE SPACECRAFT CROSSLINK
  - HTS BASED CROSSLINK REDUCES TRANSMITTER POWER BY > 12%
- DIGITAL SIGNAL PROCESSOR FOR "SMART" COMMUNICATIONS SATELLITES
  - HTS DEMODULATORS REQUIRE 0.04% OF POWER AND 4% OF WEIGHT OF SEMICONDUCTOR SYSTEMS

HIGH TEMPERATURE SUPERCONDUCTIVITY

NASA EXPERIMENT FOR HTSSE II (LeRC/JPL)

OBJECTIVES:
- DESIGN, FABRICATE AND TEST HTS LOW NOISE RECEIVER/DOWN CONVERTER (X-BAND) USING HTS FILM TECHNOLOGY AND STATE-OF-THE-ART GaAs TECHNOLOGY
- DELIVER TWO SPACE QUALIFIED SUBSYSTEMS TO NRL FOR HTSSE II

SIGNIFICANCE:
- DEMONSTRATE SUBSYSTEM INTEGRATION OF HTS FILMS WITH ACTIVE GaAs MICROWAVE INTEGRATED CIRCUITS
- POTENTIALLY ENHANCES EXISTING PERFORMANCE IN SUBSYSTEM BY REDUCING NOISE FACTOR BY 1 dB AND INCREASING LOCAL OSCILLATOR NOISE FIGURE BY 4X

NASA APPLICATIONS: SPACECRAFT TRANSPONDERS, GROUND STATION RECEIVERS

MILESTONES
- 6/91 - SUBMIT "WHITE PAPER"
- 9/91 - SELECTION OF EXPERIMENT
- 12/92 - DELIVERY OF PROTOTYPE
- 1/94 - DELIVERY OF TWO SPACE QUALIFIED SUBSYSTEMS
- 95/96 - LAUNCH
HIGH TEMPERATURE SUPERCONDUCTIVITY

PROPOSED NRL/HTSSE-II EXPERIMENT
JOINT LeRC/JPL EFFORT

CURRENT HTS PROGRAM - SENSORS

OBJECTIVE: To develop and demonstrate sensor applications of HTS thin film technology

- Extend performance of Josephson junction devices
- Low noise, sensitive transition-edge resistive and kinetic inductance IR bolometers
- Improve radiometers using high frequency communications technology

PROGRAM RESOURCES INSUFFICIENT FOR DEVICE DEVELOPMENT

IR BOLOMETERS

APPROACH: YBCO or TBCCO films on very thin substrates

APPLICATION: Thermal emission spectroscopy of atmospheres/surfaces of outer planets

MISSION REQUIREMENTS: Range 10-1000um, > 10 year mission requires passive cooling & T(det)>70K

PRESENT TECHNOLOGY: 4 x 10^{-9} D - thermopile

RESULTS TO DATE: 4 x 10^{-6} D*

CHALLENGES: Reduce noise & time constant (resistive), HTS SQUID magnetometer (inductance)

GOAL: > 10^{-10} D* @ 70-90K, single elements or arrays

JOSEPHSON JUNCTION DEVICES

APPROACH: Develop all YBCO SNS microbridges (edge junction weak link) for oscillators & mixers, BaBIO SIS tunnel junctions for mixers

APPLICATIONS: SNS THz local oscillator & mixer for submm wave astronomy (ground-based observatories & flight missions - 5M1S, LDR); SQUID's for planetary magnetic field probes, high speed signal processing

PRESENT TECHNOLOGY: LTS devices

CHALLENGES: Device geometries & film growth techniques

BENEFITS: Increased operating temperature & frequency range (THZ) of active J-J devices

RADIOMETRY

APPROACH: Develop low noise receiver (LNR) and electronic beam steering (phased array antenna feed) for radiometry

APPLICATION: LEO and GEO radiometry at 94-200 GHz

PRESENT TECHNOLOGY: LTS receivers; large, gimbal mounted steerable dish antennas

BENEFITS: Large aperture for GEO, mechanical stability for sensitive LEO platforms

CHALLENGES: Develop HTS J-J based mixers and SQUID type phase shifters; Improve HTS film quality to extend low Rs into submm region

STATUS: Conceptual phase
CURRENT HTS PROGRAM - CRYOGENIC APPLICATIONS

OBJECTIVES:

- To develop and demonstrate cryocooler applications of HTS technology
- Reduce parasitic heat loads and cryogen boiloff using HTS current leads
- Damp out cooler-generated vibrations at focal plane array
- Improve reliability and efficiency of cryoturbopumps using passive magnetic bearings

PROGRAM RESOURCES INSUFFICIENT FOR DEVELOPMENT BEYOND INDICATED STATUS

HTS CURRENT LEADS FOR THERMAL ISOLATION

APPROACH: Exploit low thermal conductivity and R+O properties of HTS ceramics

APPLICATION: Missions requiring LHe cooling (SAFIRe, AXAFS, SIRTF)

BENEFITS: Extension of mission life, grounding of FPA; improve S/N by 10-100x

MATERIALS: Adequate for low current applications

STATUS: Prototype low current leads fabricated and environmentally tested; goal is 1996 space experiment

VIBRATION DAMPING

APPROACH: Exploit low thermal conductivity and R+O properties of HTS ceramics

APPLICATION: Missions requiring LHe cooling (SAFIRe, AXAFS)

PRESENT TECHNOLOGY: Back-to-back coolers and compensating electronics

BENEFITS: Enhanced precision imaging; passive approach; damping over wide frequency range

MATERIALS: Adequate damping capability

STATUS: Lab demo of X10 greater damping at 77K with non-optimum material & magnet geometry

PASSIVE MAGNETIC BEARINGS

APPROACH: Exploit magnetic levitation force and stiffness properties of HTS ceramics

PRESENT TECHNOLOGY: Gas bearings

BENEFITS: Increased turbocompressor efficiency (reduced power & heat leak); improved reliability and lifetime

MATERIALS: Levitation pressure adequate, some improvement in stiffness needed

NON-NASA: Recent advances in materials stimulated large effort to develop bearings for rotating machinery

STATUS: University grant to develop materials (CUA); contract to evaluate materials (Cornell)

HIGH TEMPERATURE SUPERCONDUCTIVITY

TECHNOLOGY FIRSTS

- AMONG FIRST IN U.S. TO DEPOSIT HIGH QUALITY YBCO FILMS BY LASER ABLATION

- FIRST TEST OF HTS Kα-BAND CIRCUIT (MICROSTRIP RESONATOR)

- FIRST TEST OF AN HTS ANTENNA ARRAY (2X2)

- DEVELOPED NOVEL EFFECTIVE TECHNIQUE (Br ETCH) FOR SURFACE CLEANING AND PASSIVATION OF HTS FILMS

- FABRICATED FIRST ALL HTS EDGE-GEOMETRY MICROBRIDGES UTILIZING NON-SUPERCONDUCTING YBCO BARRIER LAYERS

- AMONG FIRST TO DEMONSTRATE HTS TRANSITION-EDGE BOLOMETERS
HIGH TEMPERATURE SUPERCONDUCTIVITY

CURRENT FUNDING (FY 90-92)

NASA CENTERS HAVE THE NECESSARY FACILITIES ON-SITE OR READY ACCESS TO UNIVERSITY, GOVERNMENT OR INDUSTRIAL RESOURCES

STATE-OF-THE-ART CAPABILITIES

- MATERIALS PREPARATION (THIN FILMS AND BULK)
- MATERIALS CHARACTERIZATION (CRITICAL CRYOGENIC PROPERTIES)
- DEVICE DEVELOPMENT (LABORATORY MODEL TO SYSTEM VALIDATION MODEL)
- DEVICE TESTING (LABORATORY DEMONSTRATION TO FLIGHT QUALIFICATION)
HIGH TEMPERATURE SUPERCONDUCTIVITY

HIGH TEMPERATURE SUPERCONDUCTIVITY
R&T BASE AUGMENTATION

- NEW INITIATIVES

- MILESTONES / RESOURCES

ORBITER/ACTS HTS 20GHz PHASED ARRAY ANTENNA
FLIGHT EXPERIMENT

LEWIS XMTR

JSC TEST LAB

STEERABLE SUPERCONDUCTING RCV ANTENNA

10 KBPS@30 GHZ

20 GHZ
**ORBITER/ACTS FLIGHT EXPERIMENT OF HTS PHASED ARRAY ANTENNA**

**OBJECTIVE:**
Demonstrate functionality in space of receiver/phase array antenna subsystem with HTS critical components

**APPROACH:**
Transmission of voice data from ground terminal to ACTS (30 GHz) and relay to 20 GHz receiver/antenna in shuttle bay

Reuse of orbiter hardware from proposed 1995 Ka-band ACTS experiment to greatly reduce cost

Phased array antenna: 9 subarrays, each with 4x4 microstrip patches (144 total elements), 16 way HTS power combiner, HTS filter and cooled GaAs LNA

**WORK BREAKDOWN:**
- LeRC - Antenna Development, Fabrication & Test, ACTS Ground Station
- JSC - Orbiter Manifest, Orbiter Interface, Antenna Controller

**CHALLENGES:**
- Array size and complexity, uniform HTS films, integration of hybrid circuits, packaging, ground testing of full array

**MAJOR MILESTONES:**
- FY93 - Antenna Module Fab & Test; FY94 - Flight Hardware Fab;
- FY95 - Flight Hardware Test, Assemble in Shuttle Bay; FY96 - Launch

**FUNDING:**
- FY93 - $1.1M, FY94 - $1.2M, FY95 - $1.2M, FY96 - $0.2M

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**HTS DIGITAL SIGNAL PROCESSOR**

**OBJECTIVE:**
Exploit HTS digital electronics for the next generation of smart communications satellites

**APPROACH:**
Develop a reproducible Josephson junction process for analog-to-digital (A/D) converters, mixers, and complimentary electronics that will ultimately lead to a 1 Gbps QPSK modulator, followed by a demodulator as the technology matures.

**APPLICATIONS:**
High data rate deep space communications and advanced satellite communications

**BENEFITS:**
- HTS digital signal processors are 10 times faster than state-of-the-art semiconductor technology
- HTS demodulators require only 0.04% of the power of semiconductor subsystems
- HTS demodulators require only 4% of the weight of semiconductor subsystems
- Large increase in number of channels

**STATUS:**
- TRW demonstrated a HTS four bit A/D converter which operated at about 50K
- FUJITSU demonstrated a low Tc 24,000 junction microprocessor
- Reproducible, manufacturable HTS Josephson junctions are evolving

**CHALLENGES:**
- Processing of reliable, high density Josephson junctions

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**DIGITAL SIGNAL PROCESSOR**

**RECEIVER ELECTRONICS**
**SIGNAL PROCESSOR**
**DEMODULATOR**
**TRANSMITTER ELECTRONICS**

**SATELLITE TRANSPONDER**
RESOURCES WITH AUGMENTATION

CODE RC FUNDING IN $M

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* REPROGRAMMED FROM COMMUNICATIONS BASE

AUGMENTED HTS PROGRAM MILESTONES & RESOURCE ALLOCATION

COMMUNICATIONS* (RADIOMETER)

SENSORS

CRYOGENIC APPLICATIONS

Δ - Current Program
Δ - "3X Budget" Augmentation
Δ - "Strategic Plan" Augmentation

* Assumes reprogrammed $0.6M
RELATED NON-NASA HTS EFFORTS

- DoD - DARPA, SDIO, NAVY, AIR FORCE, ARMY
  - FY 91 - EST $56M FOR HTS
  - AREAS OF MUTUAL INTEREST - RF COMMUNICATIONS, SENSORS, HIGH FIELD MAGNETS, PASSIVE MAGNETIC BEARINGS
  - DARPA & SDIO FUNDING SNS JOSEPHSON JUNCTION EFFORT AT JPL ($390K IN FY91)
  - COLLABORATION IN SPACEBORNE CRYOCOOLER DEVELOPMENT
- DoE - MUTUAL INTEREST IN POWER TRANSMISSION, ENERGY STORAGE
- UNIVERSITY - MANY LABORATORIES
- INDUSTRY - MANY LARGE COMPANIES AND SMALL ENTREPRENEURIAL COMPANIES
- FOREIGN - LARGE JAPANESE AND EUROPEAN EFFORTS

INTERAGENCY PROGRAMS

- NASA/NRL MOU FOR HTSSE PROGRAM
  COLLABORATION ON SPACE APPLICATIONS OF HTS AND CRYOCOOLER TECHNOLOGY
- LeRC/ARGONNE MOU
  JOINT STUDIES OF ENERGY STORAGE AND POWER TRANSMISSION
- GSFC/NTIS - HTS IR BOLOMETER DEVELOPMENT
- PRELIMINARY NASA LeRC/USAF DISCUSSIONS FOR COLLABORATION ON HTS PHASED ARRAY ANTENNA DEVELOPMENT AND ORBITER/ACTS FLIGHT EXPERIMENT
- POTENTIAL NASA/SDIO COLLABORATION ON FOCAL PLANE ARRAY SIGNAL PROCESSING
## SUPERCONDUCTING FOCAL PLANE ARRAY SIGNAL PROCESSING

### ON-ARRAY SIGNAL PROCESSING DEVELOPMENT STATUS (DEMONSTRATED WITH Nb)

- **IR DETECTOR (TRW)**
  - 10-25 µm
  - 10X better than best IR bolometer
- **12 BIT A-D CONVERTER (Westinghouse)**
- **8 BIT SIGNAL PROCESSOR (Fujitsu, Hitachi)**

### DEVELOPMENT GOALS (SDIO)

- **END-TO-END DEMONSTRATION OF FPA ASSEMBLY WITH Nb (4K) DEVICES**
- **NEXT GENERATION - NbN (10K)**
- **FUTURE - BaKBo (30K)**

### TECHNICAL CHALLENGE

- On-Array memory (20K or more)

### SIGNIFICANT ADVANTAGES OVER SEMICONDUCTOR TECHNOLOGY

- **HIGHER SPEED (> 10 X faster than GaAs)**
- **LOWER POWER (> 20 X less than Si)**
- **FIBER OPTIC DATA LINES (X10 fewer)**
- **GREATLY REDUCED HEAT LOAD**
- **GREAT POTENTIAL FOR WIDE AREA IR AND OTHER FREQUENCIES**

### ISSUES

- **RECENT ADVANCES IN MATERIALS AND DEMONSTRATION OF ORDER OF MAGNITUDE OR MORE IMPROVEMENT IN PERFORMANCE AMPLIFIES NEED FOR AN AGGRESSIVE NASA HTS R&T PROGRAM**

- **STABLE BASE FUNDING LEVEL IS NEEDED - PRESENT FUNDING COMES MOSTLY FROM DIVERSE, SHORT TERM SOURCES**

- **INADEQUATE TO DEVELOP APPLICATIONS TO LEVEL OF READINESS FOR TRANSFER TO FOCUSED PROGRAMS AND NASA USERS**