NASA-TM-108655

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

N93-20775
Unclas
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(NASA-TM-108655) SSTAC/ARTS REVIEW OF THE DRAFT INTEGRATED TECHNOLOGY PLAN (ITP). VOLUME 8: AEROTHERMODYNAMICS AUTOMATION AND ROBOTICS (A/R) SYSTEMS SENSORS, HIGH-TEMPERATURE SUPERCONDUCTIVITY (NASA) 318 p

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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Aerothermodynamics
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SSTAC/ARTS

Aerothermo-Dynamics

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

AEROTHERMODYNAMICS

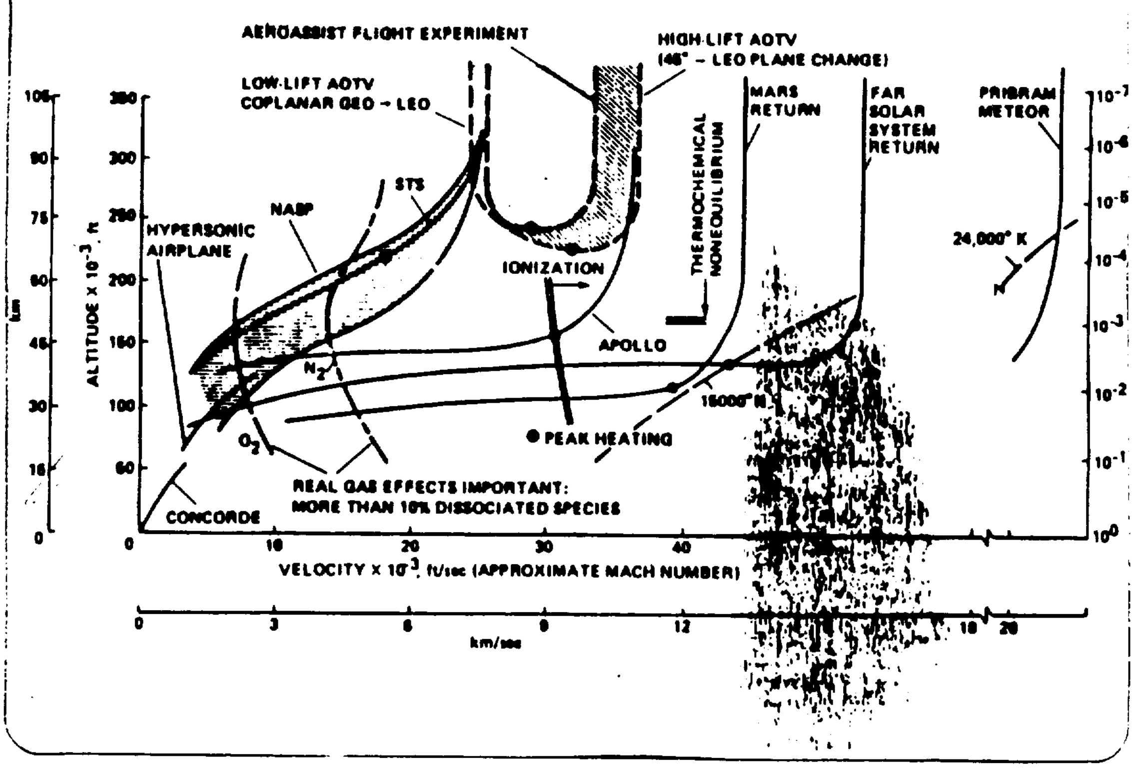
AN ELEMENT OF THE BASE RESEARCH AND TECHNOLOGY PROGRAM

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

- 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

AEROTHERMODYNAMICS BASE R&T PROGRAM

OAET

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

OAET

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
  - AEROLOADS 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

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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

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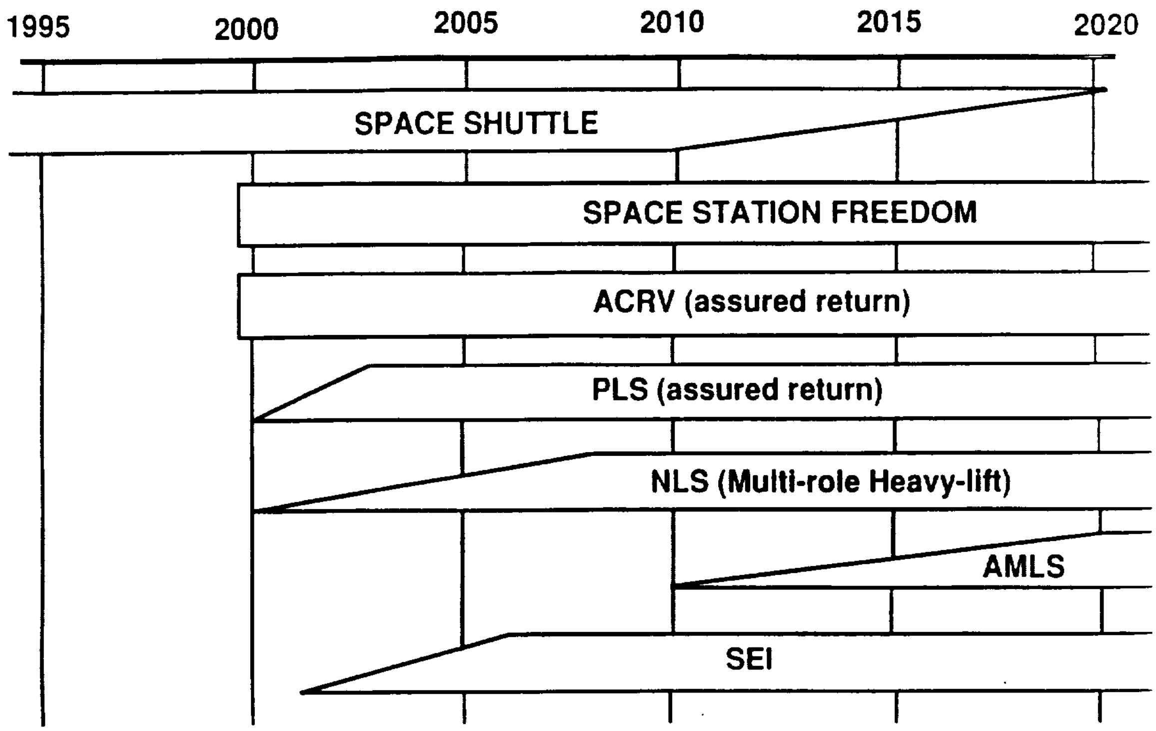
SPACE TRANSPORTATION ARCHITECTURE OPTIONS



AEROTHERMODYNAMICS BASE R&T PROGRAM

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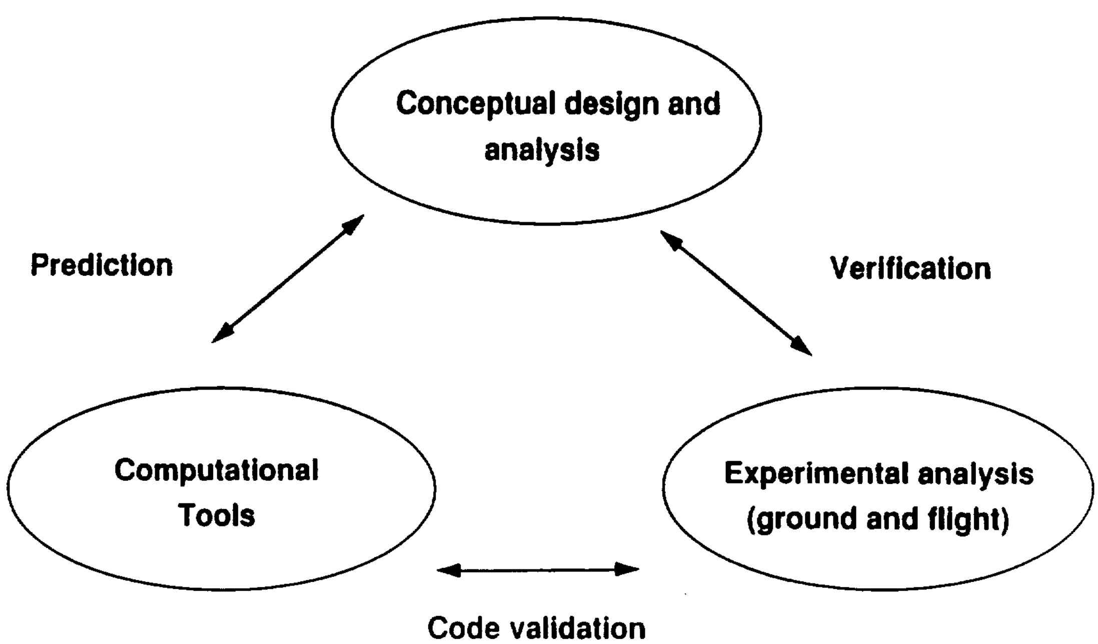
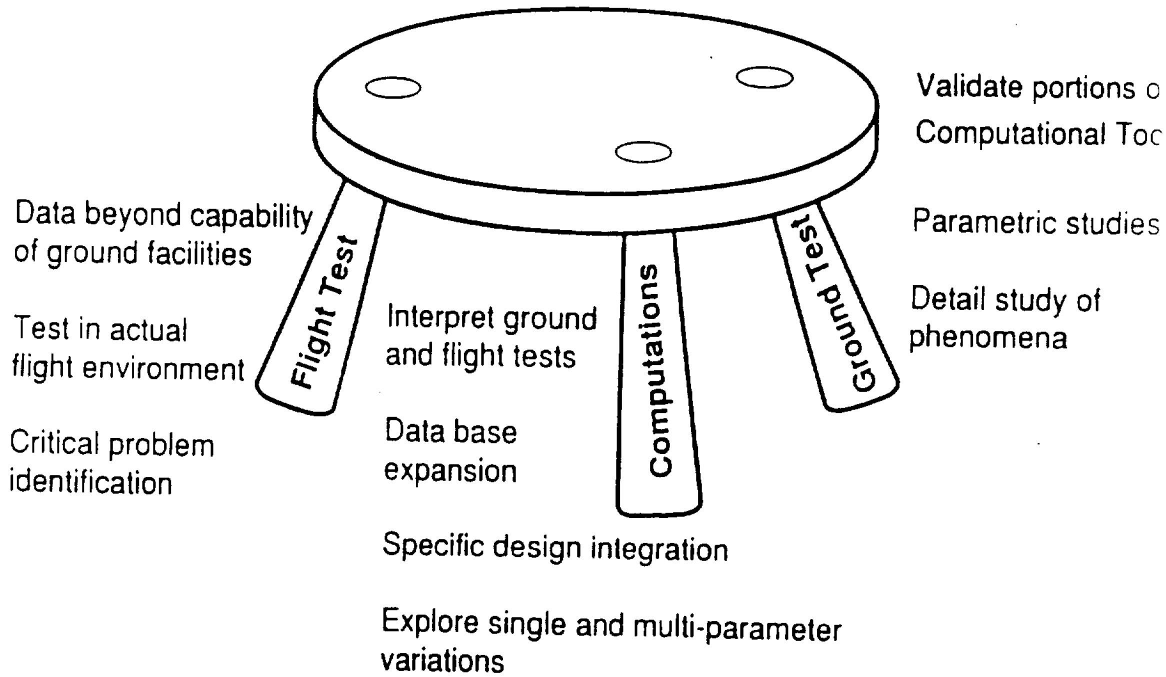
INVOLVES THE FULL INTEGRATION OF THREE ESSENTIAL, UNIQUE CAPABILITIES TO PROVIDE THE DESIGN CRITERIA FOR FUTURE VEHICLES



AEROTHERMODYNAMICS BASE R&T PROGRAM

MUTUALLY DEPENDENT TECHNOLOGIES



AEROTHERMODYNAMICS BASE R&T PROGRAM

AUGMENTATION PLAN

CAPABILITY DEVELOPMENT

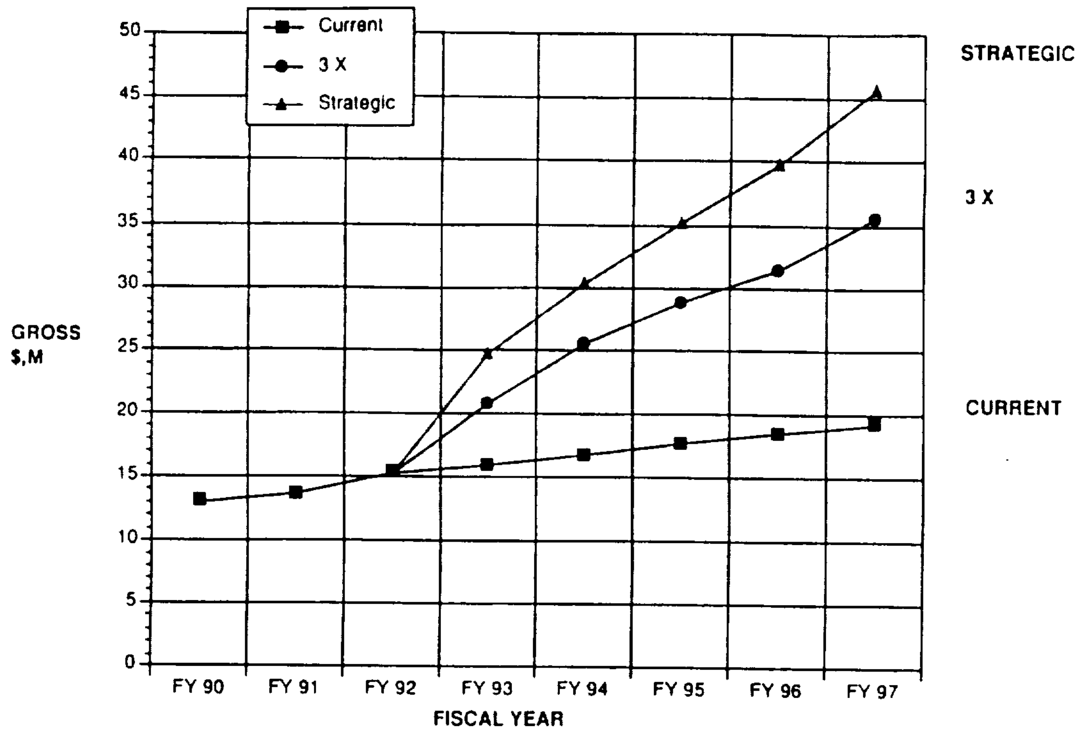
- COMPUTATIONAL TOOL DEVELOPMENT
- EXPERIMENTAL RESEARCH/COMPUTATIONAL VALIDATION
- FACILITIES RESEARCH

CAPABILITY APPLICATION

- CONFIGURATION ASSESSMENT

AEROTHERMODYNAMICS BASE R&T PROGRAM
BUDGET IMPLICATIONS

OAET



AEROTHERMODYNAMICS BASE R&T PROGRAM

RUNOUT OF AUGMENTED(STRATEGIC) PROGRAM ($M)

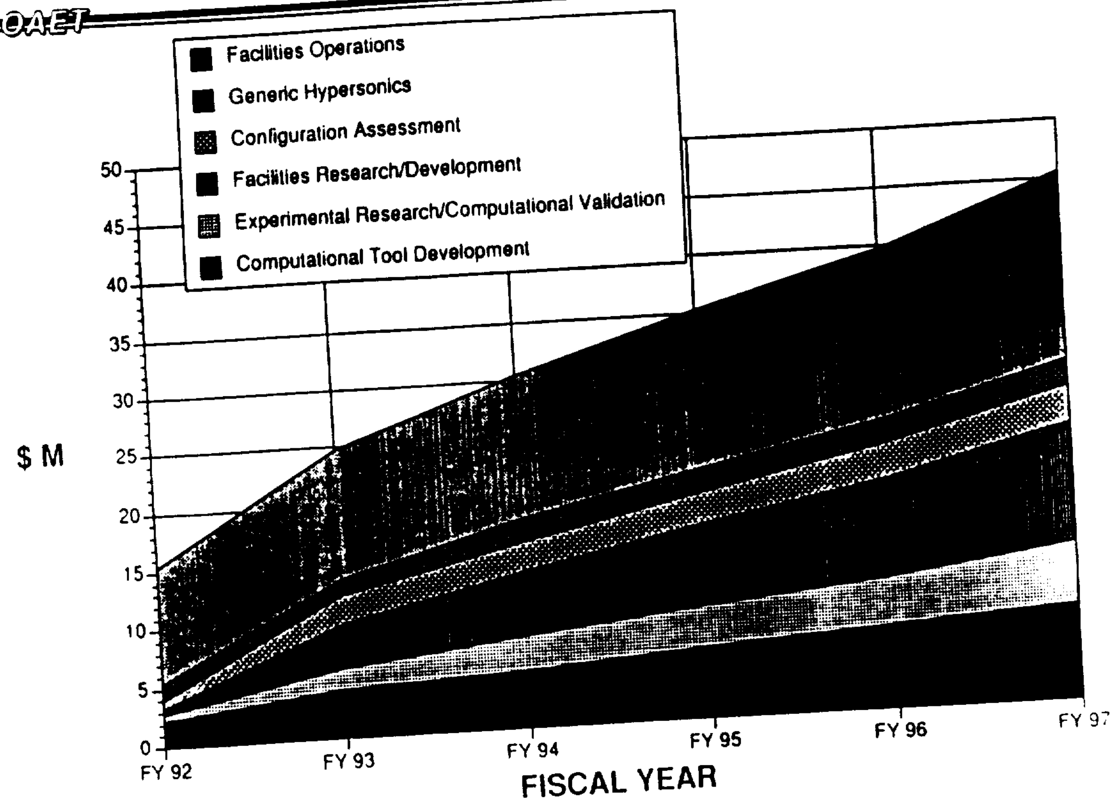
OAET

SUB-ELEMENT RESOURCES (NET)	FY 92	FY 93	FY 94	FY 95	FY 96	FY 97
Computational Tool Development	2.2	4.2	4.9	6.2	7.2	8.2
Experimental Research/ Computational Validation	0.7	1.8	3.0	3.5	4.2	5.5
Facilities Research/ Development	0.4	3.8	5.6	7.1	8.4	10.0
Configuration Assessment	0.7	2.5	2.6	2.7	3.0	3.3
Generic Hypersonics	*1.4*	*1.4*	*1.9*	*2.0*	*2.1*	*2.2*
Total (Net)	5.4	13.7	18.0	21.5	24.9	29.2
Total (Gross)	15.4	24.8	30.4	35.2	39.8	45.6

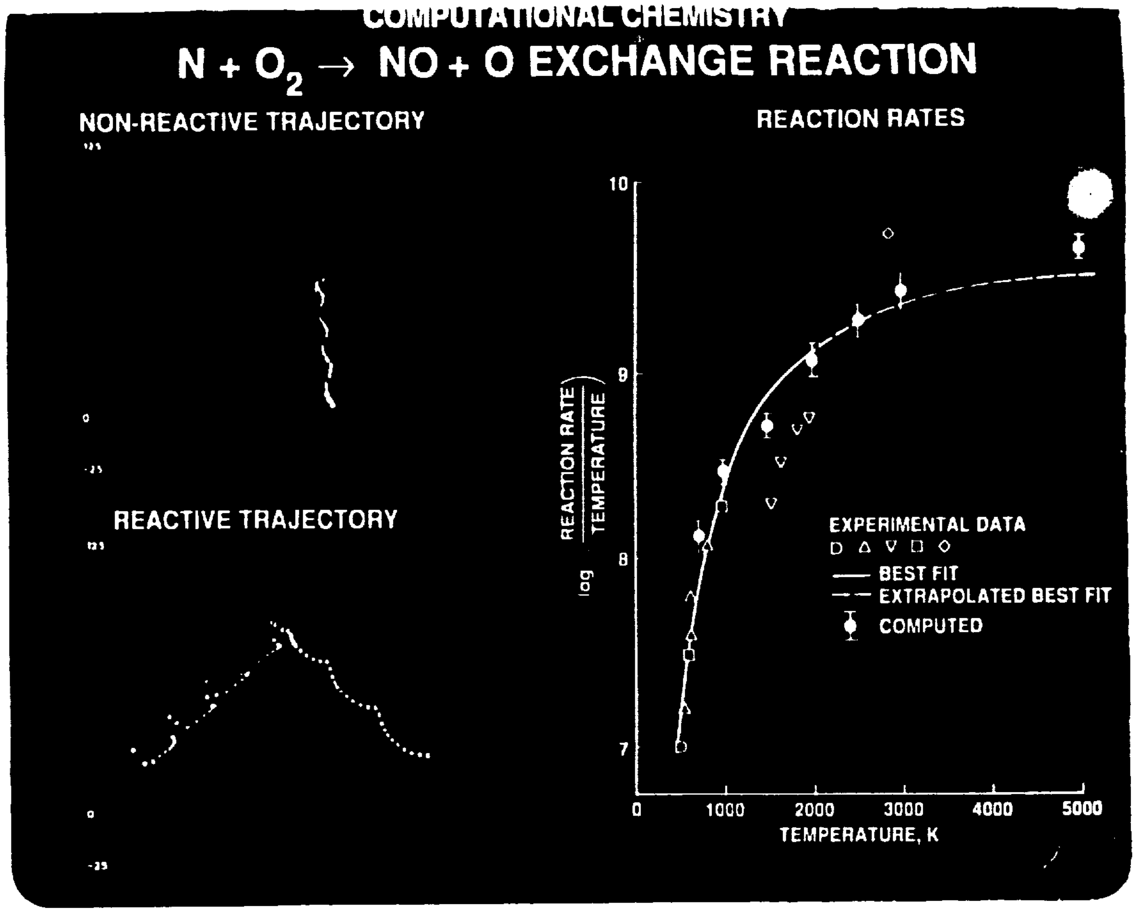
AEROTHERMODYNAMICS BASE R&T PROGRAM

RUNOUT OF AUGMENTED(STRATEGIC) PROGRAM ($M)

OAET



COMPUTATIONAL TOOL DEVELOPMENT



AEROTHERMODYNAMICS
COMPUTATIONAL TOOL DEVELOPMENT

OAET

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

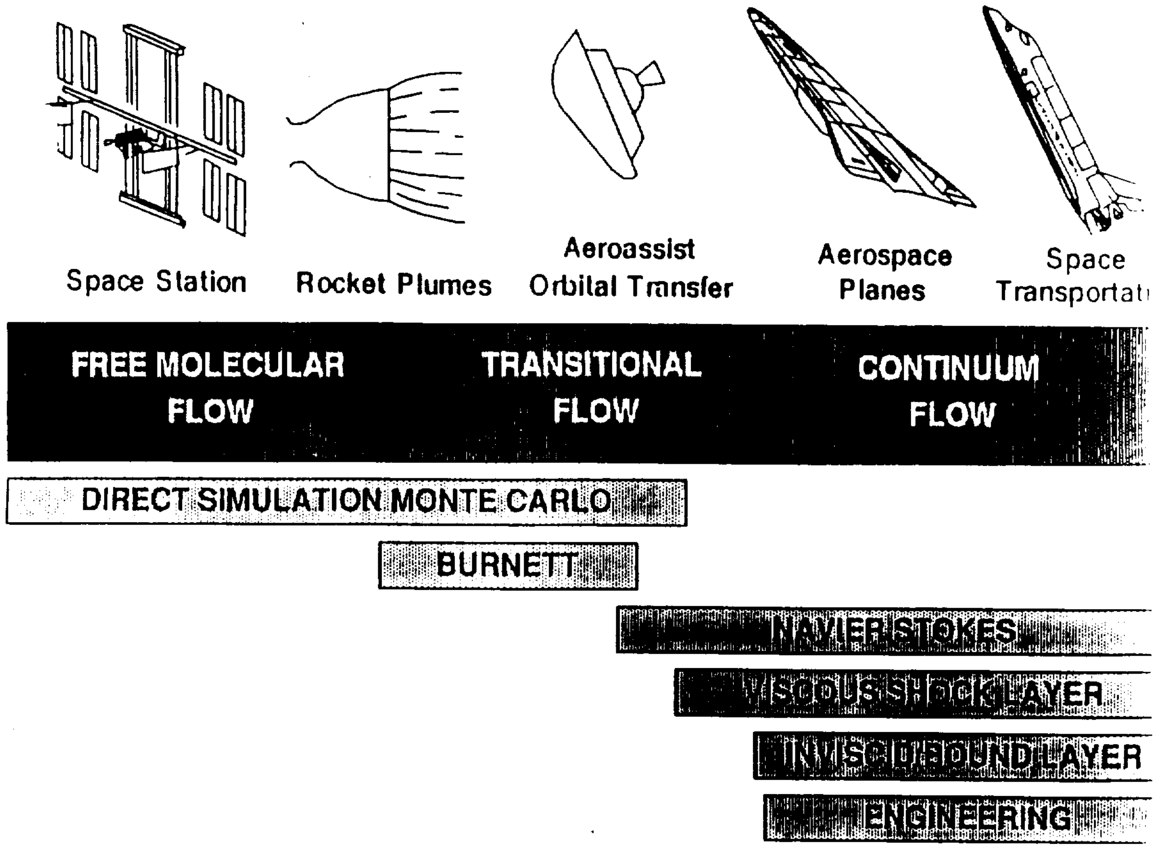
CURRENT PROGRAM S-O-A

3-D CONFIGURATIONS, EQUILIBRIUM GAS COMPUTATIONS "IN-HAND"; THERMOCHEMICAL, NON-EQ SOLUTIONS AND DSMC TECHNIQUES NOT VALIDATED; PHYSICAL PROCESS MODELIN 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

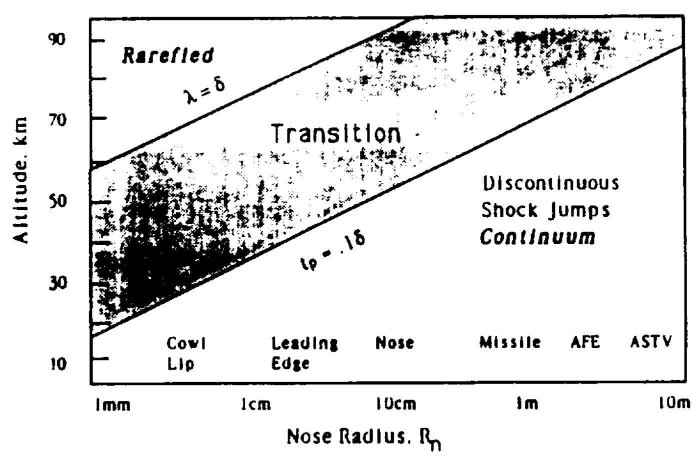
AEROTHERMODYNAMIC CFD CODE DEVELOPMENT



AEROTHERMODYNAMICS BASE R&T PROGRAM

OAET

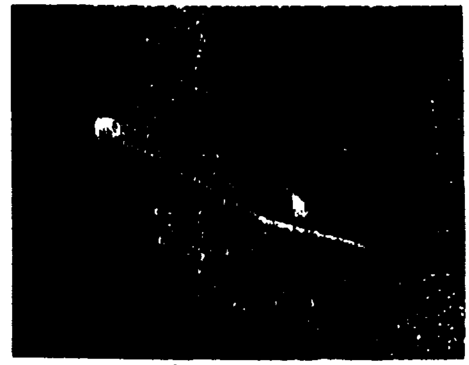
Low Density Flow Regimes



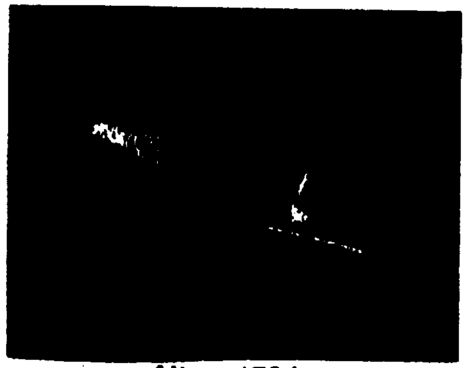
- "LOW DENSITY EFFECTS" ARE A FUNCTION OF THE LOCAL LENGTH SCALE AND THE LOCAL MEAN FREE PATH LENGTH (LOCAL KNUDSEN NUMBER, $Kn = \lambda/L$)
- THEY ARE NOT JUST A HIGH ALTITUDE PHENOMENA

DSMC SIMULATION OF FLOW ABOUT SHUTTLE ORBITER

Alt = 120 km



Alt = 100 km



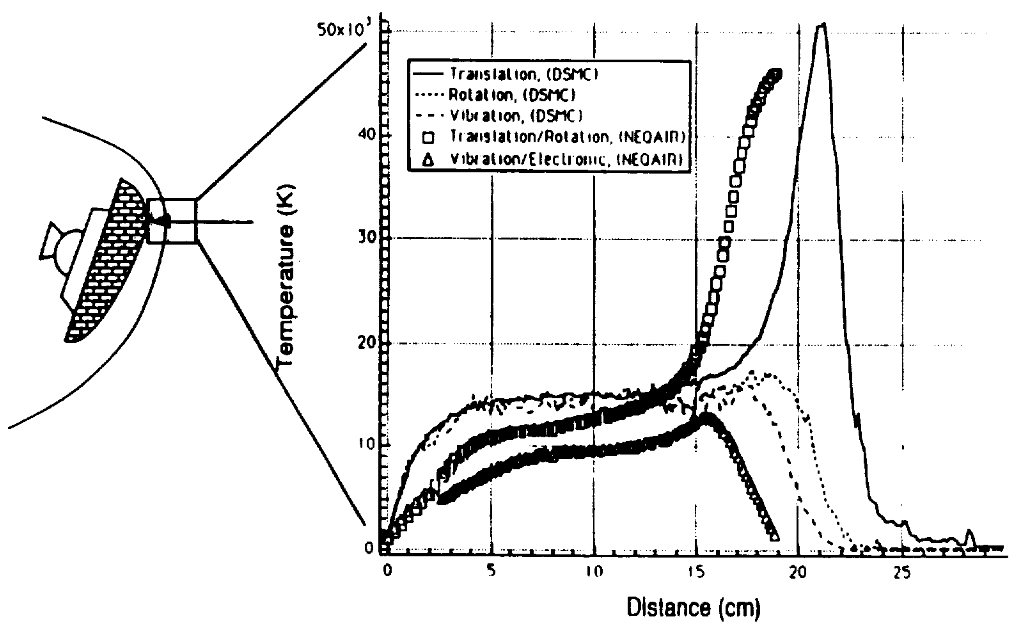
Alt = 170 km

BLUE = Molecules unaffected by vehicle

RED = Molecules that have struck the surface

YELLOW = Blue in collision with red or yellow

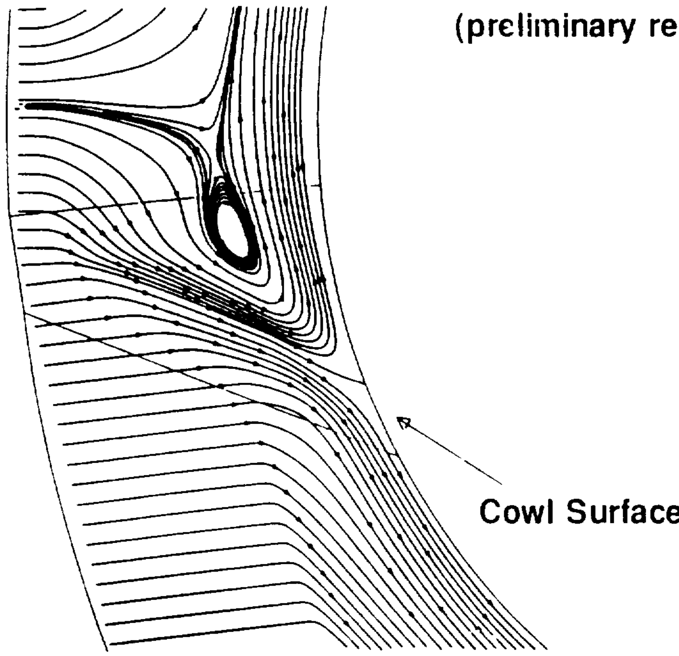
Stagnation Line Profiles of the AFE

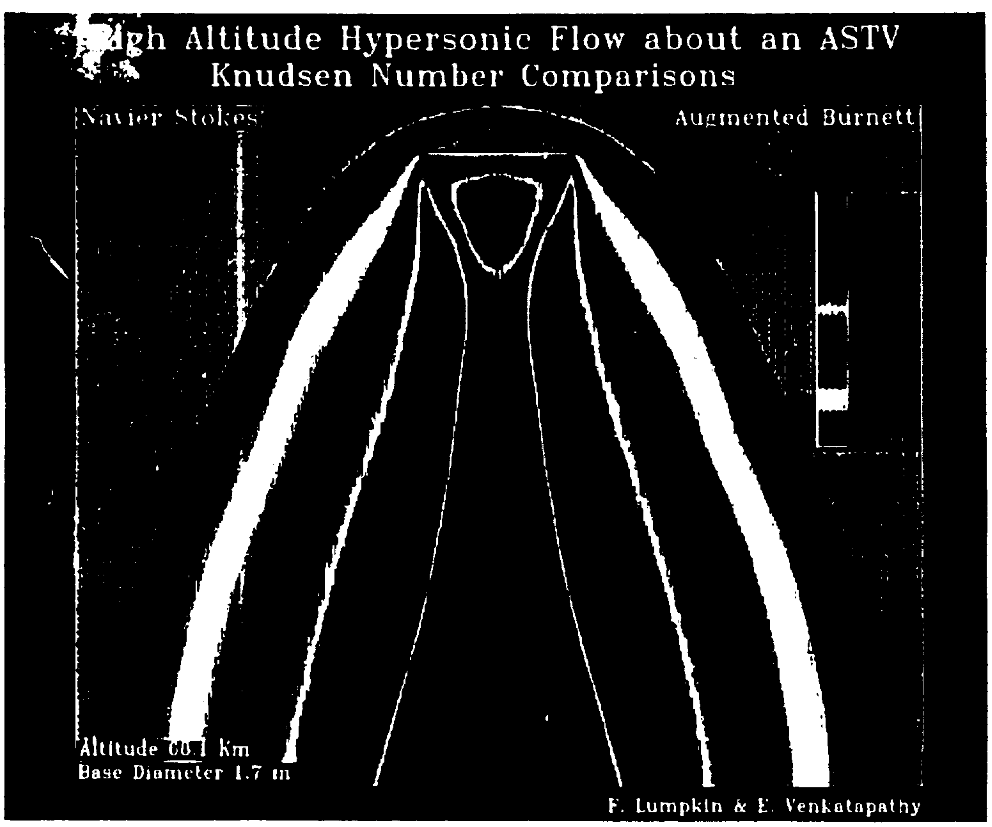


WJF 6/11/91 (18)

Streamlines Near Shock-Shock Interaction

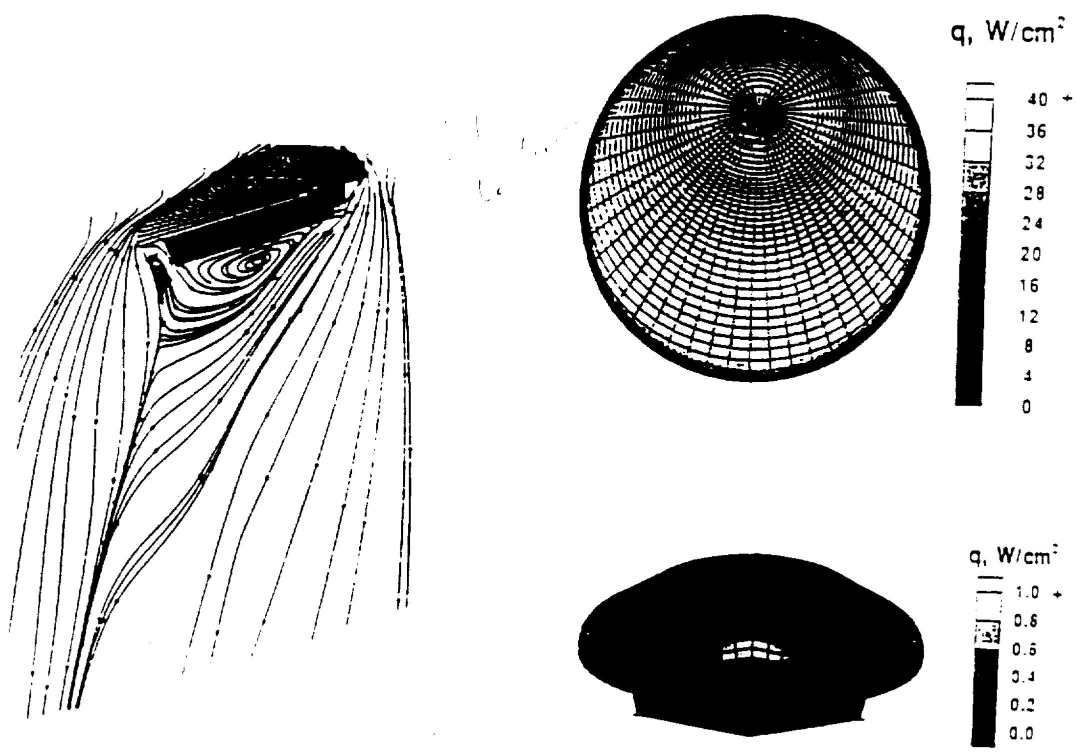
(preliminary results)



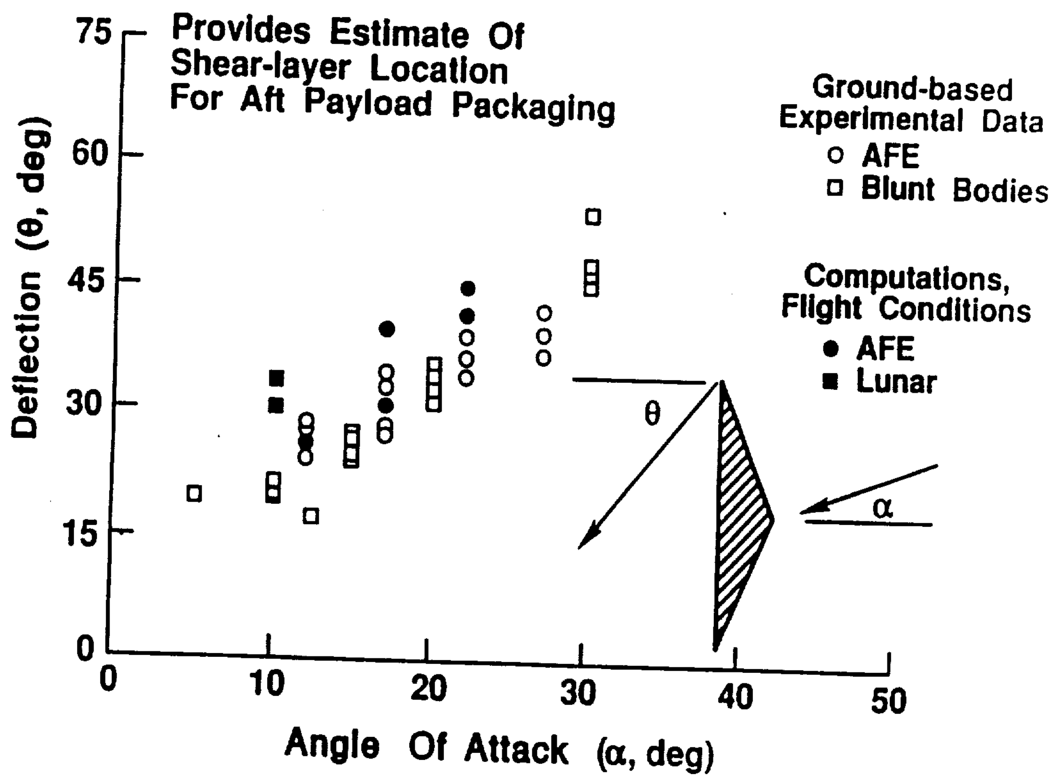


AFE SURFACE HEATING

$V_\infty = 9.3$ km/s $h = 75$ km $\alpha = -5°$

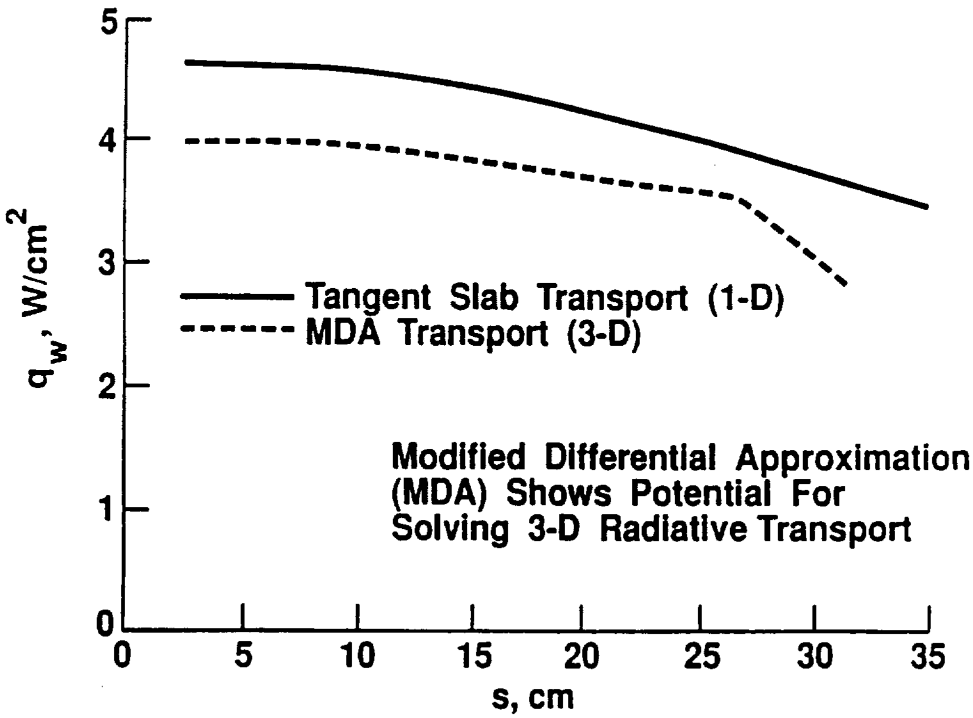


WAKE FLOWS FOR AEROBRAKES SHEAR-LAYER DEFLECTION ANGLES



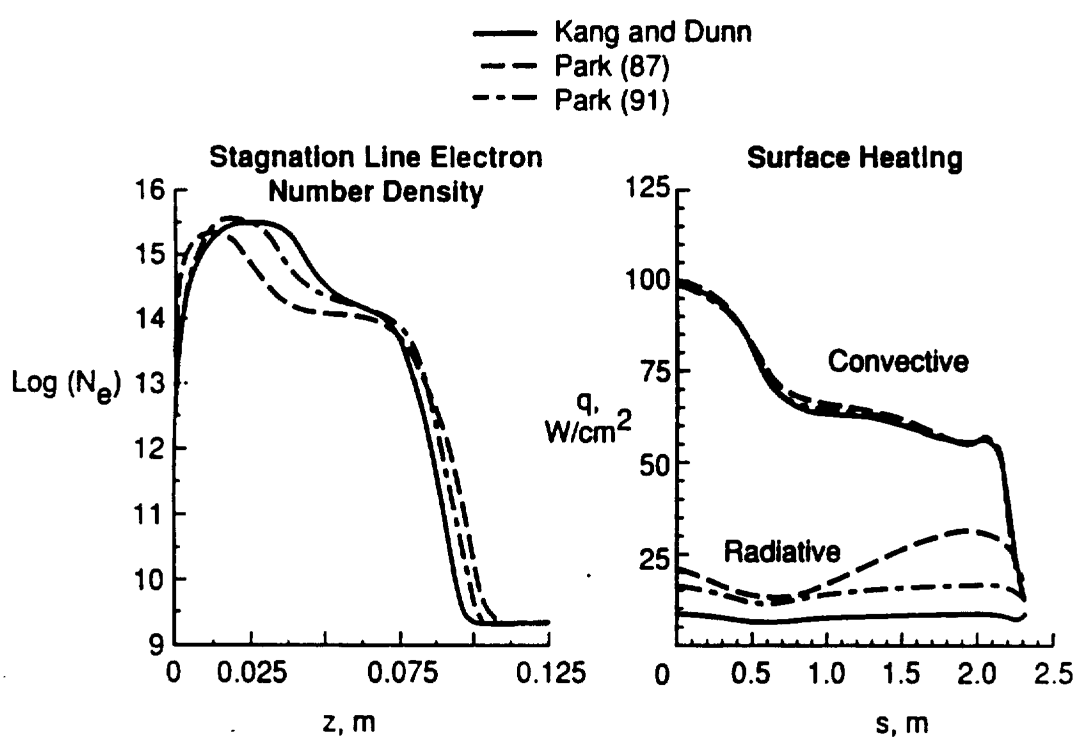
ADVANCEMENT IN RADIATIVE TRANSPORT

AFE Equivalent Sphere Radiative Flux

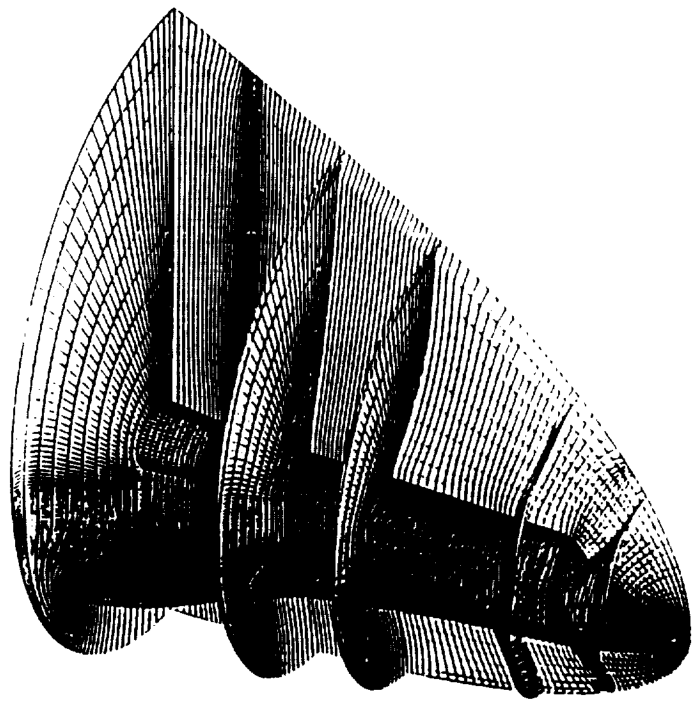


COMPARISON OF THREE CHEMICAL REACTION RATE SETS

V_∞ = 12 km/sec, altitude = 80 km, R_{nose} = 1.08 m

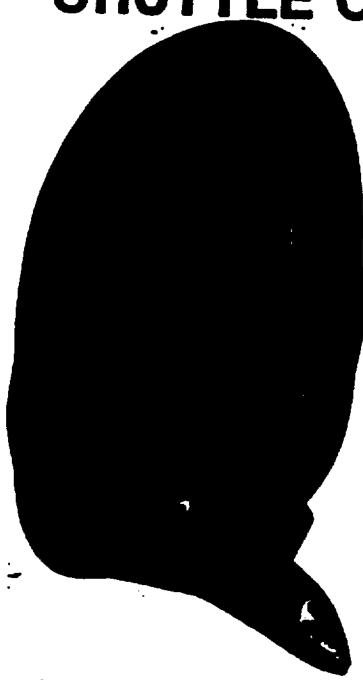


Initial Shuttle Surface and Volume Grid

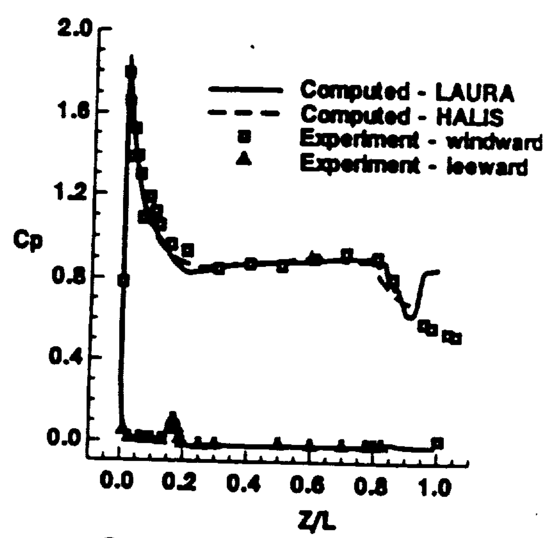


SHUTTLE ORBITER PRESSURE

Mach = 7.4, α = 40°

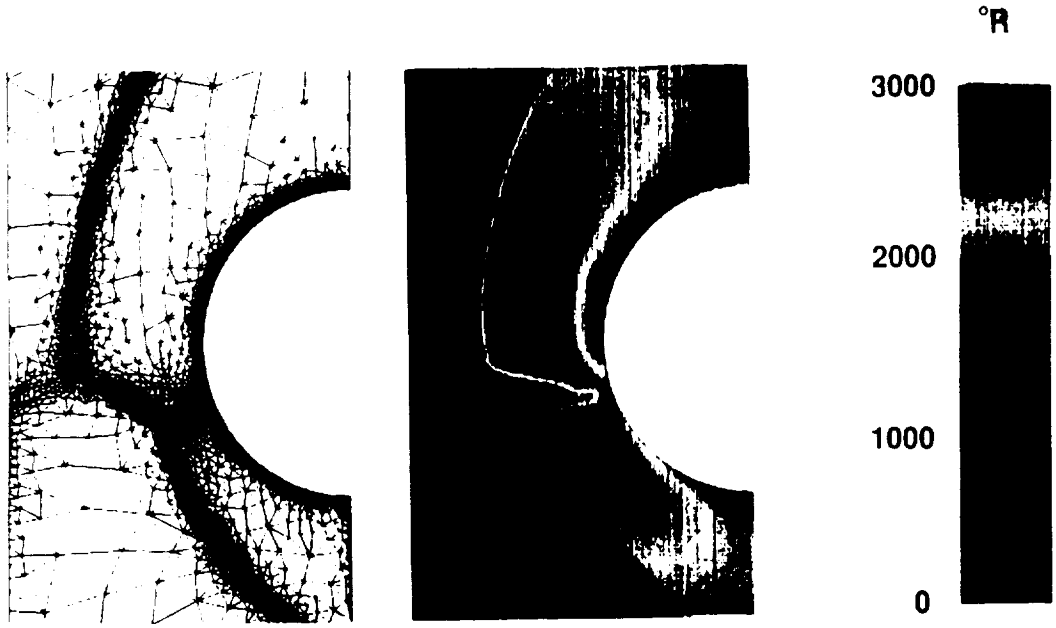


Flowfield and Surface Pressure

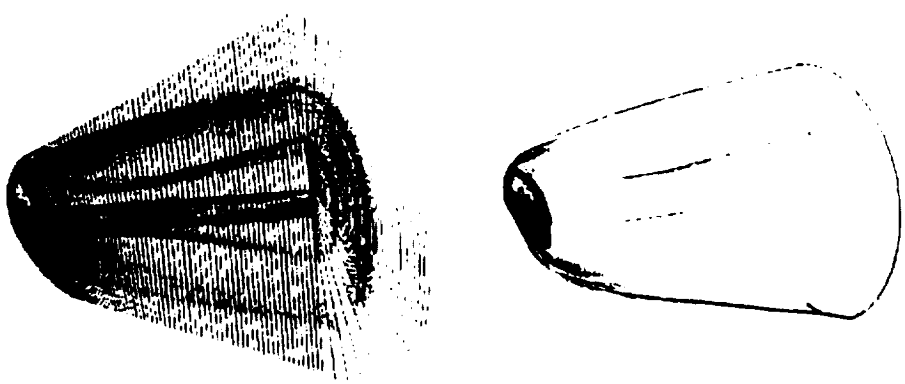


Centerline Surface Pressure

FLOW TEMPERATURE



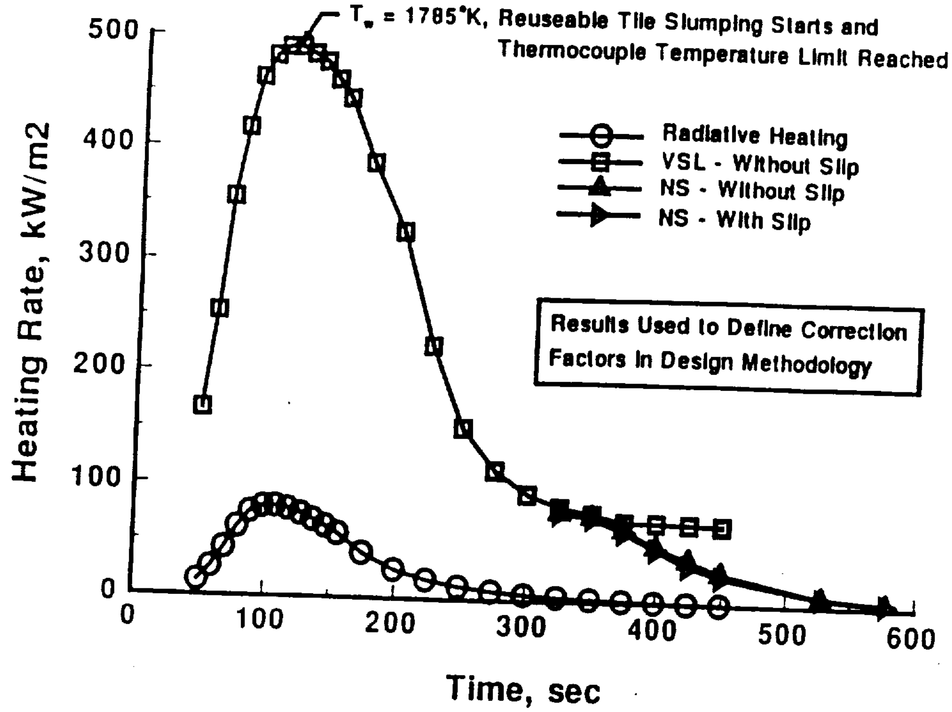
AFE Afterbody

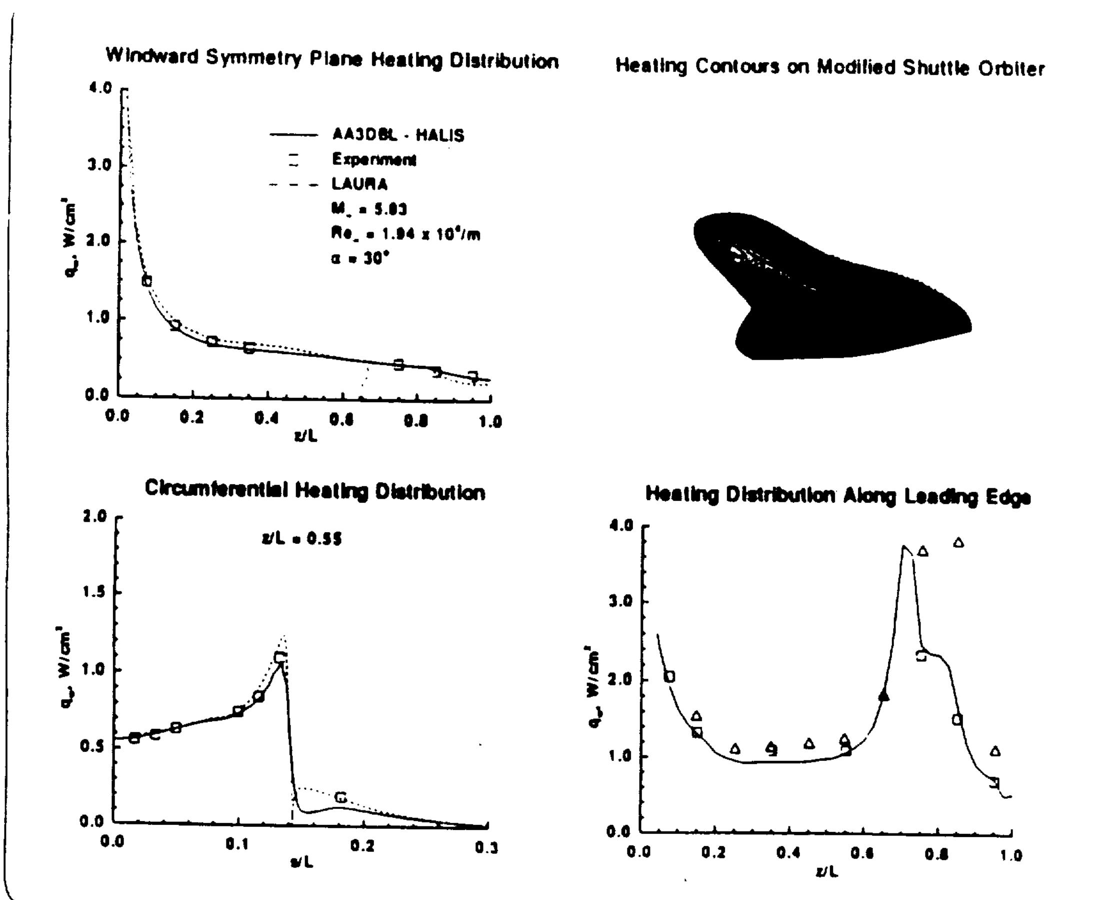


Adapted grid
based on density, pressure
and temperature gradients

Temperature contours obtained
using adapted grid showing
recompression shock and shear layer

STAGNATION POINT HEATING RATE ON AFE





VEHICLE SYNTHESIS ENGINEERING TOOLS

TECHNOLOGY NEEDS

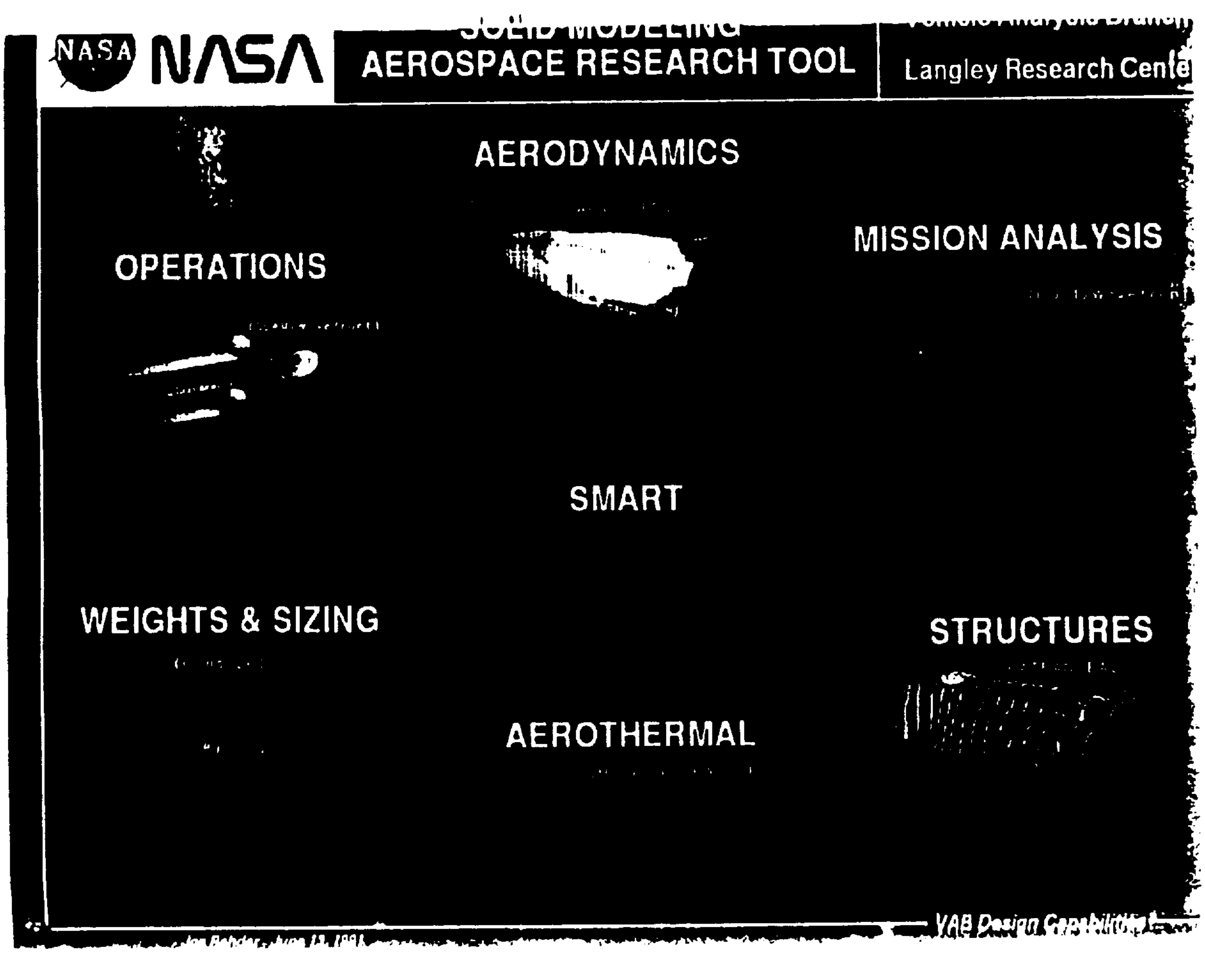
ROBUST AND RAPID AERODYNAMIC AND AEROTHERMODYNAMIC ENGINEERING METHODS FOR CONFIGURATIONAL DESIGN AND OPTIMIZATION

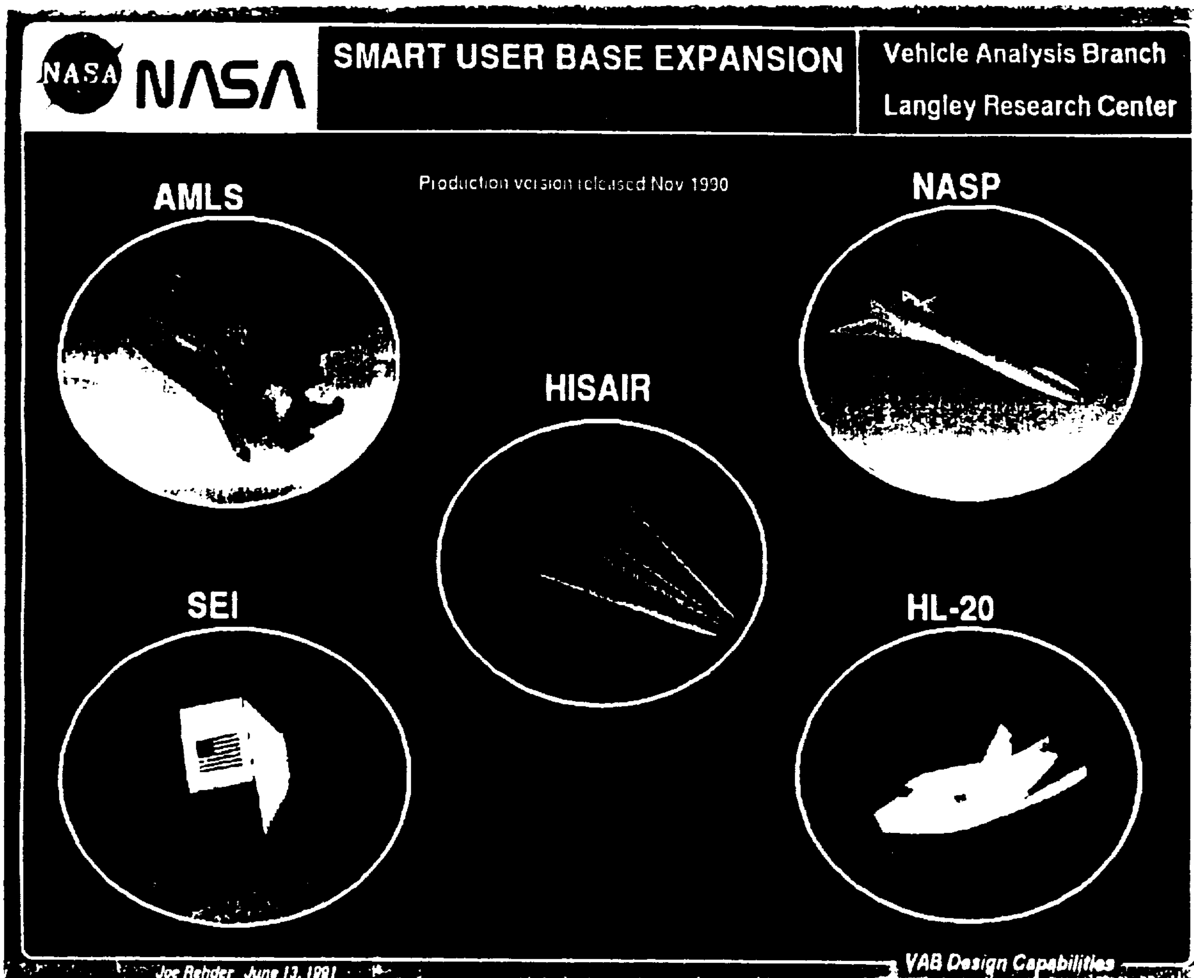
CURRENT PROGRAM S-O-A

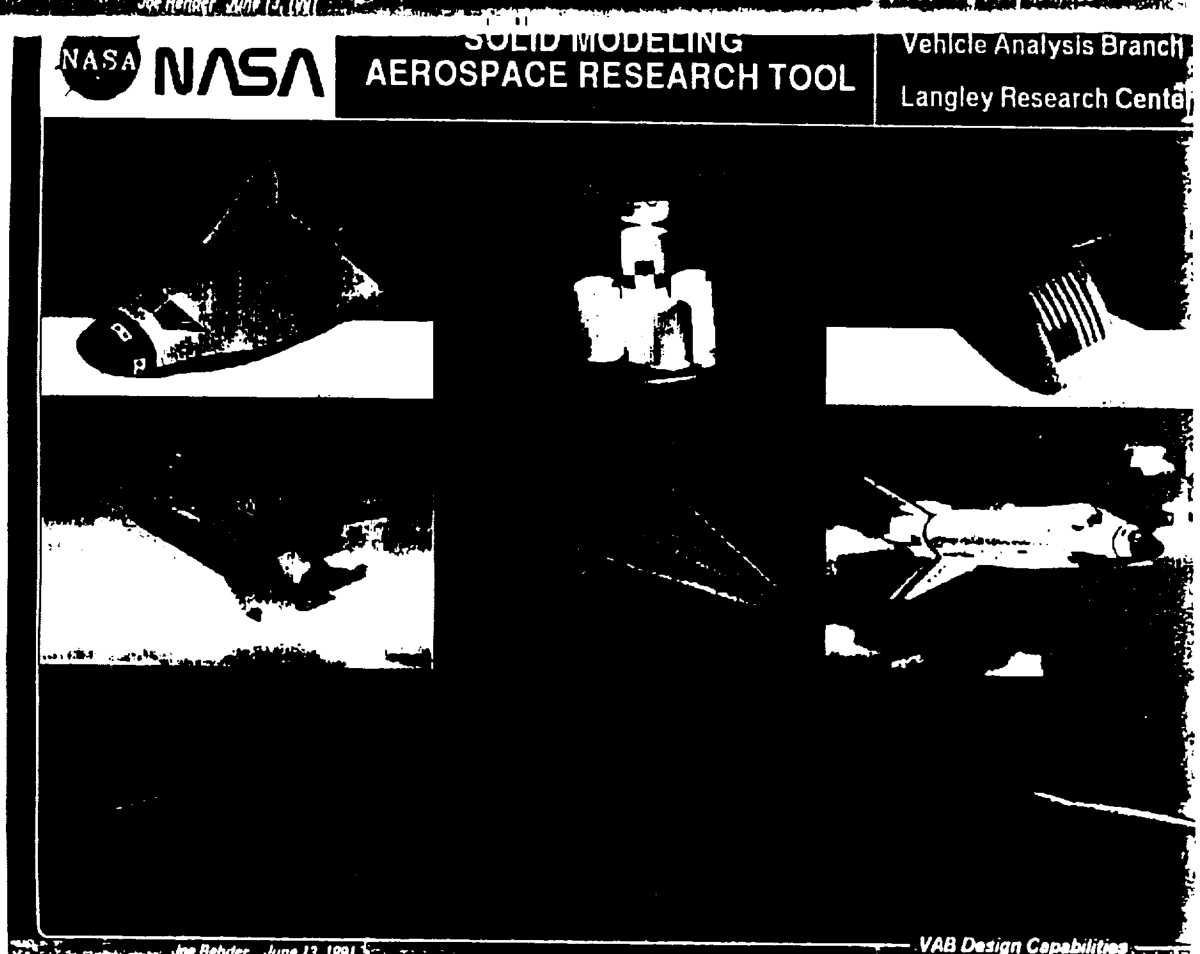
"APAS" - AERODYNAMIC PRELIMINARY ANALYSIS SYSTEM - ENGINEERING CODE DEVELOPED WITH CAPABILITIES TO PREDICT VEHICLE AERO/HEATING. REQUIRES IMPROVEMENTS IN MODELING FOR TRANSONIC REGIME AND HEATING IN HYPERSONIC REGIME

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




NASA
SMART USER BASE EXPANSION
Vehicle Analysis Branch
Langley Research Center
AMLS
Production version released Nov 1990
NASP
HISAIR
SEI
HL-20
Joe Rehder June 13, 1991
VAB Design Capabilities


NASA
SOLID MODELING
AEROSPACE RESEARCH TOOL
Vehicle Analysis Branch
Langley Research Center
Joe Rehder June 13, 1991
VAB Design Capabilities

AEROTHERMODYNAMICS COMPUTATIONAL TOOL DEVELOPMENT

OAET

FY 93	FY 94	FY 95	FY 96	FY 97

DETAILED FLOWFIELD/FLUID PROPERTIES ANALYSIS

- ▲ Enhanced Grid Generation
- ▲ High Temperature Gas Properties
- ▲ 3-D Non-Equilibrium Radiation Modeling
- ▲ 3-D Turbulence and Shear-Layer Modeling
- ▲ Complete Development of Prototype 3-D Adaptive Unstructured Mesh
- △ Coupled Nonequilibrium Radiation Model Complete
- △ Fully Coupled Flowfield and Ablation Capability

VEHICLE SYNTHESIS ENGINEERING TOOLS

- ▲ Improve the Robustness of APAS
- ▲ SMART Geometry Enhancement
- ▲ Flowfield-based Engineering Methods
- ▲ Initial Integration of Expert Systems
- △ Develop a Global Vehicle Geometry Optimization Capability
- △ Demonstration of Expert Systems/Optimization

AEROTHERMODYNAMICS BASE R&T PROGRAM

OAET

EXPERIMENTAL RESEARCH/COMPUTATIONAL VALIDATION

GROUND-BASED DATA ACQUISITION AND ANALYSIS

TECHNOLOGY NEEDS

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

CURRENT PROGRAM S-O-A

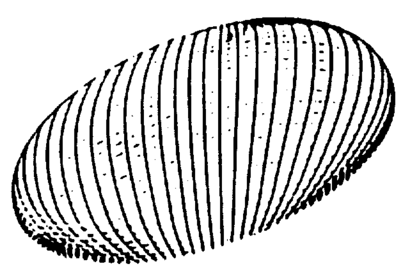
CERTAIN HYPERSONIC SIMILITUDE PARAMETERS MAY BE REPLICATED WITH WIND TUNNELS OVER LIMITED RANGES OF VALUES WITH ACCURATE MEASUREMENTS FOR ONLY GROSS FLOWFIELD AND POINTWISE SURFACE PROPERTIES. REAL GAS FACILITIES EXPAND THE PARAMETER RANGE, BUT LIMITED IN SIZE, FLOW QUALITY, AND FLOW DIAGNOSTICS

AUGMENTED PROGRAM

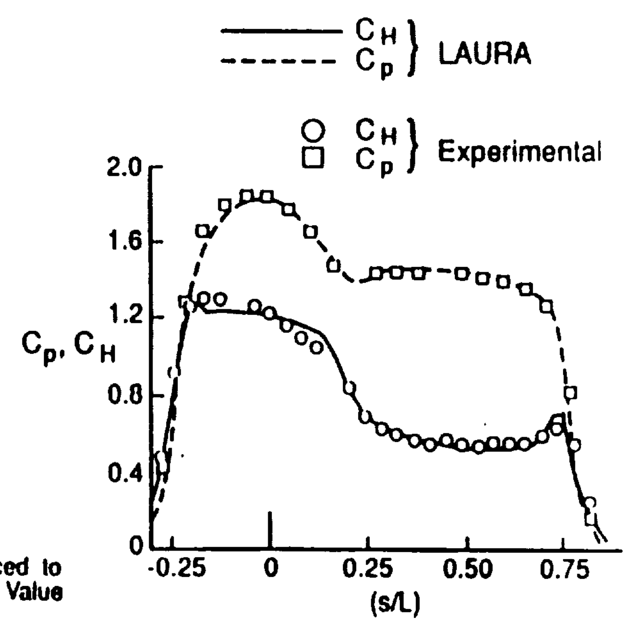
DATABASES THAT ENCOMPASE A BROADER SPECTRUM OF FLUID PHYSICS FOR
UTILIZATION OF EXISTING HIGH ENTHALPHY FACILITIES, INCREASE
TESTING IN UNIQUE, COMPLEMENTARY, NON-NASA FACILITIES
MORE AGGRESSIVE INVOLVEMENT OF CFD IN
EXPERIMENT DEFINITION

ADVANCES IN COMPUTATIONAL CAPABILITY

(Mach 10 Air, $\alpha = -5°$, $Re_L = 159{,}000$)



Surface Grid



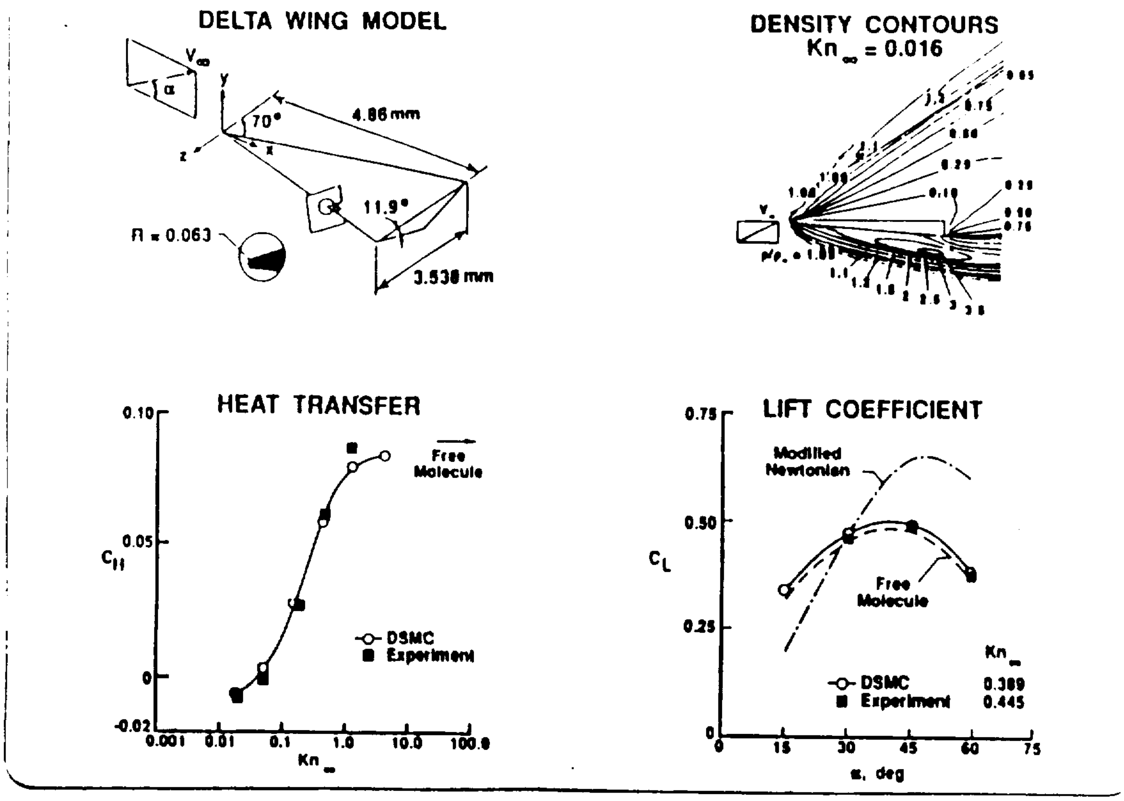
s - Arc Length in Symmetry Plane Measured from Stagnation Point

L - Base Diameter (3.67 in.)

C_p - Pressure Coefficient

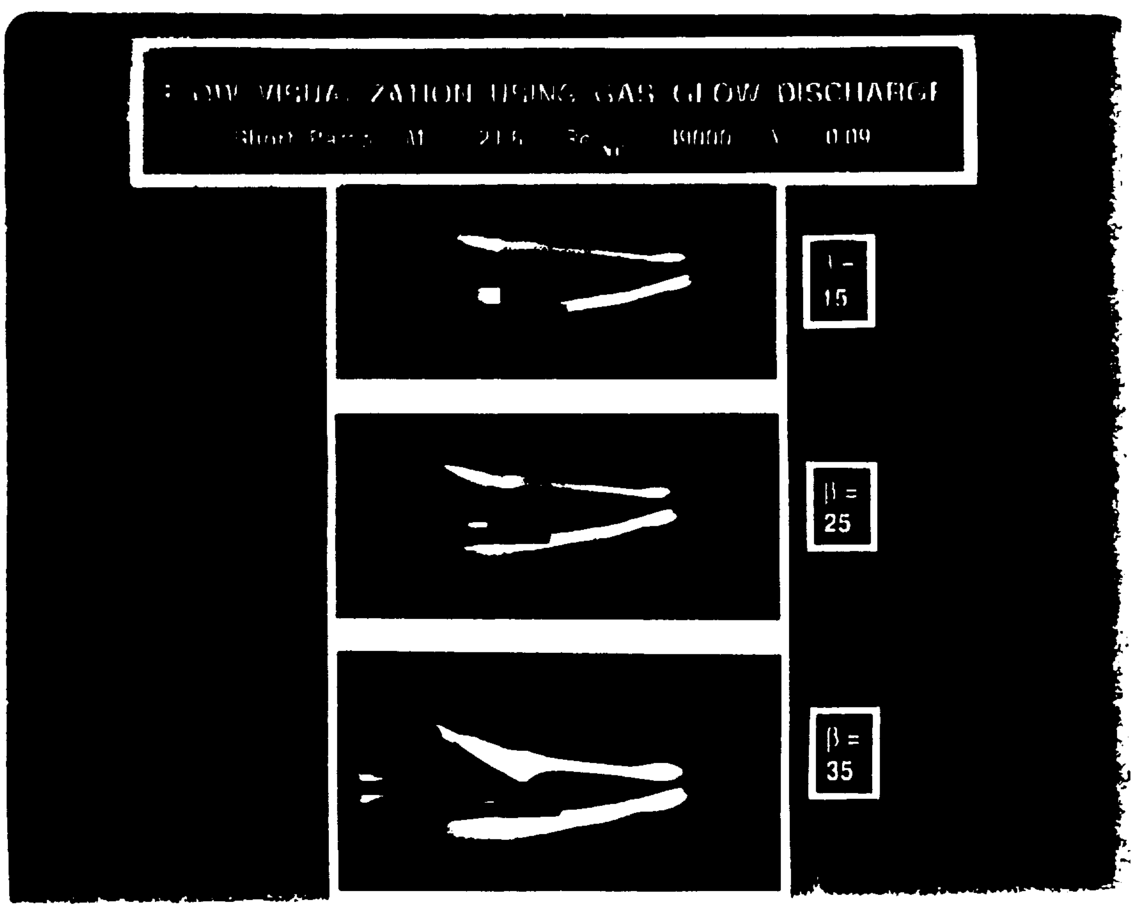
C_H - Heat Transfer Coefficient Referenced to Fay and Riddell Stagnation Point Value

HYPERSONIC RAREFIED FLOW ABOUT A DELTA WING: COMPARISON OF DSMC AND EXPERIMENT



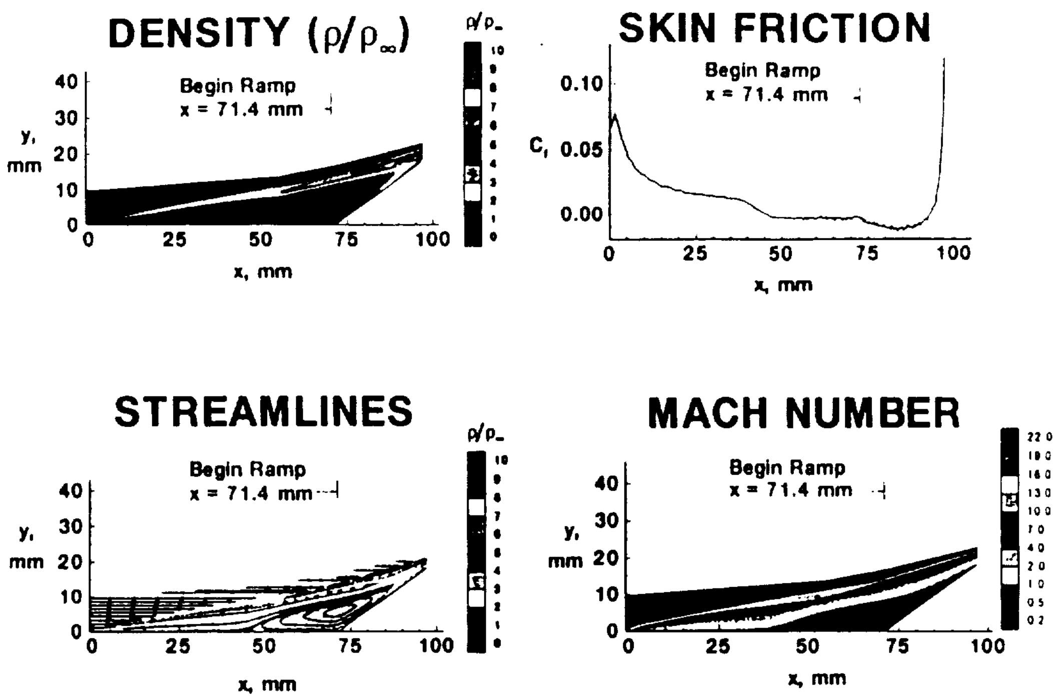
National Aeronautics and
Space Administration

NO

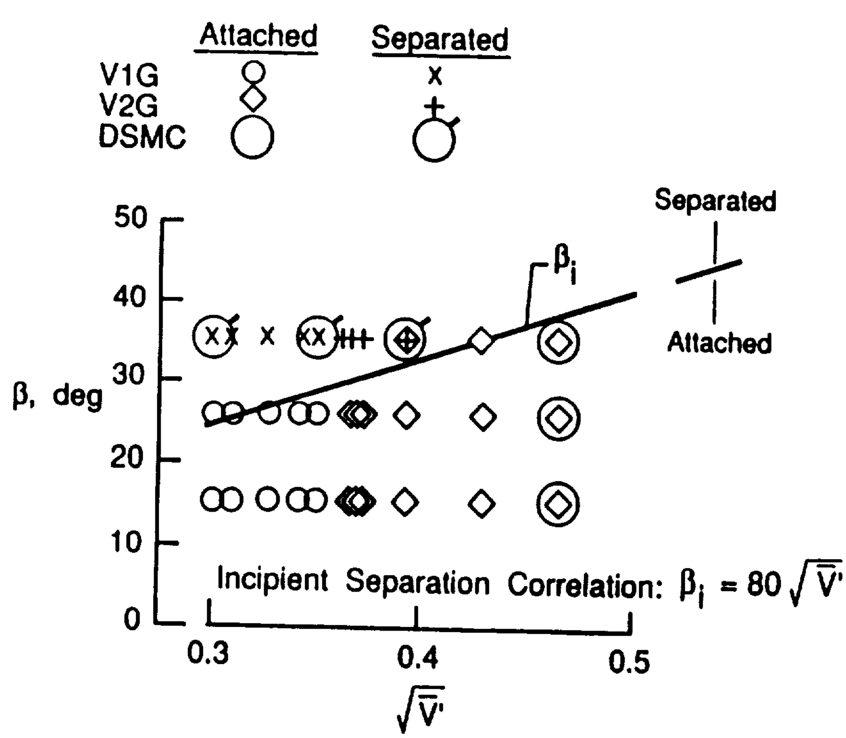


35° Ramp, $\rho_\infty = 39.12 \times 10^{-5}$

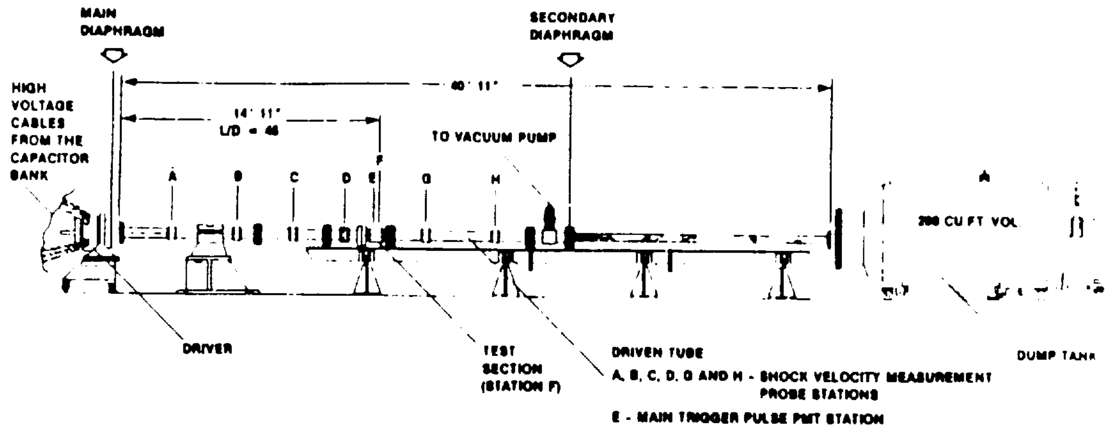
$M_\infty = 21.58$, $\lambda_\infty = 0.073$ mm, $T_W = 341$ K



COMPARISON OF EXPERIMENTAL AND SIMULATEI RESULTS FOR INCIPIENT SEPARATION



ELECTRIC ARC-DRIVEN SHOCK TUBE FACILITY

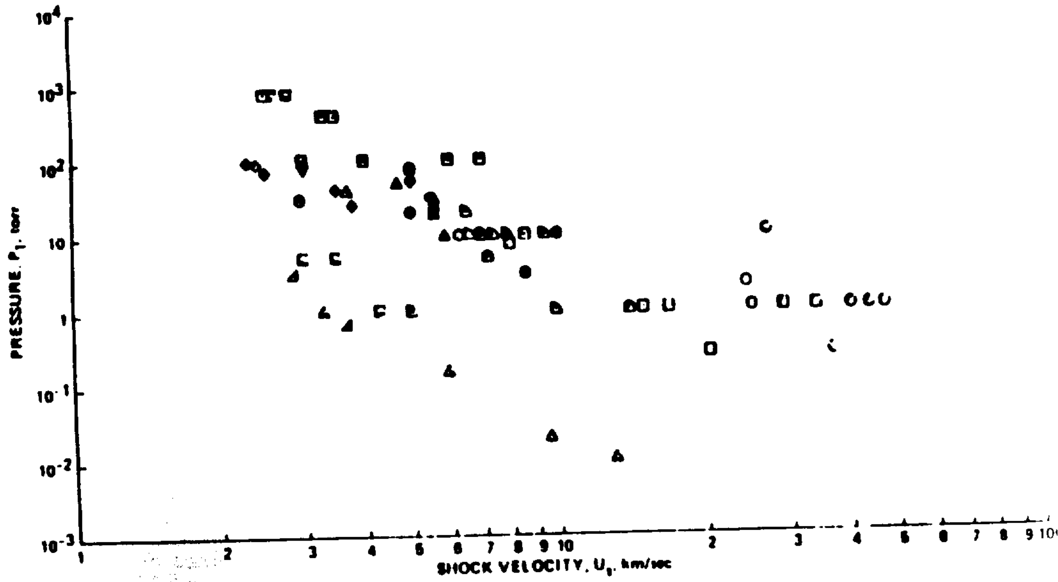


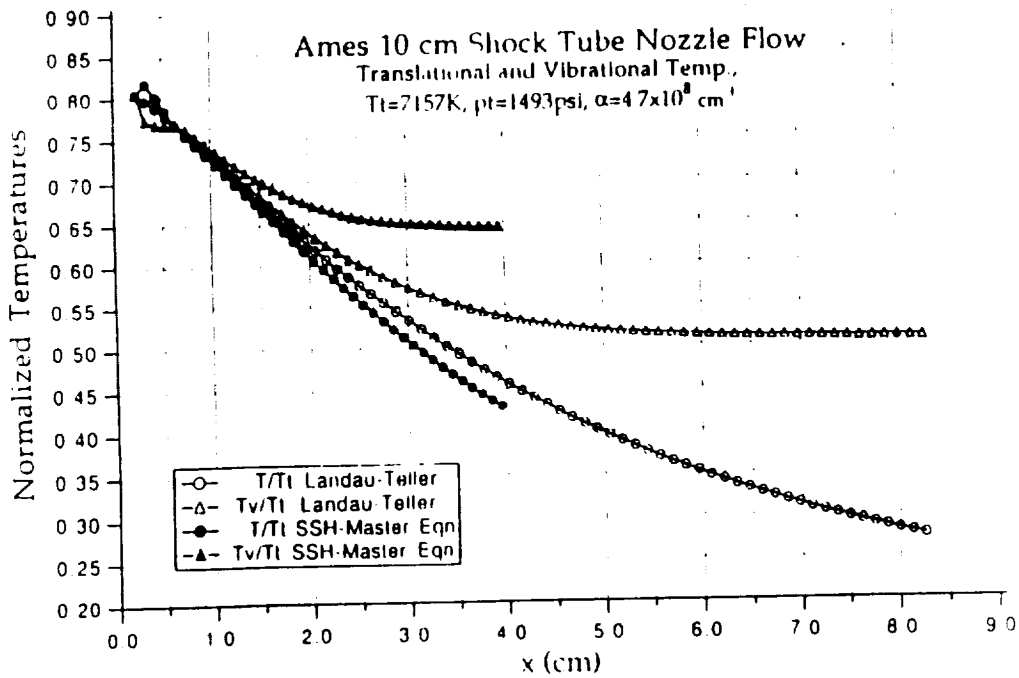
PERFORMANCE OF ELECTRIC ARC DRIVEN SHOCK TUBES

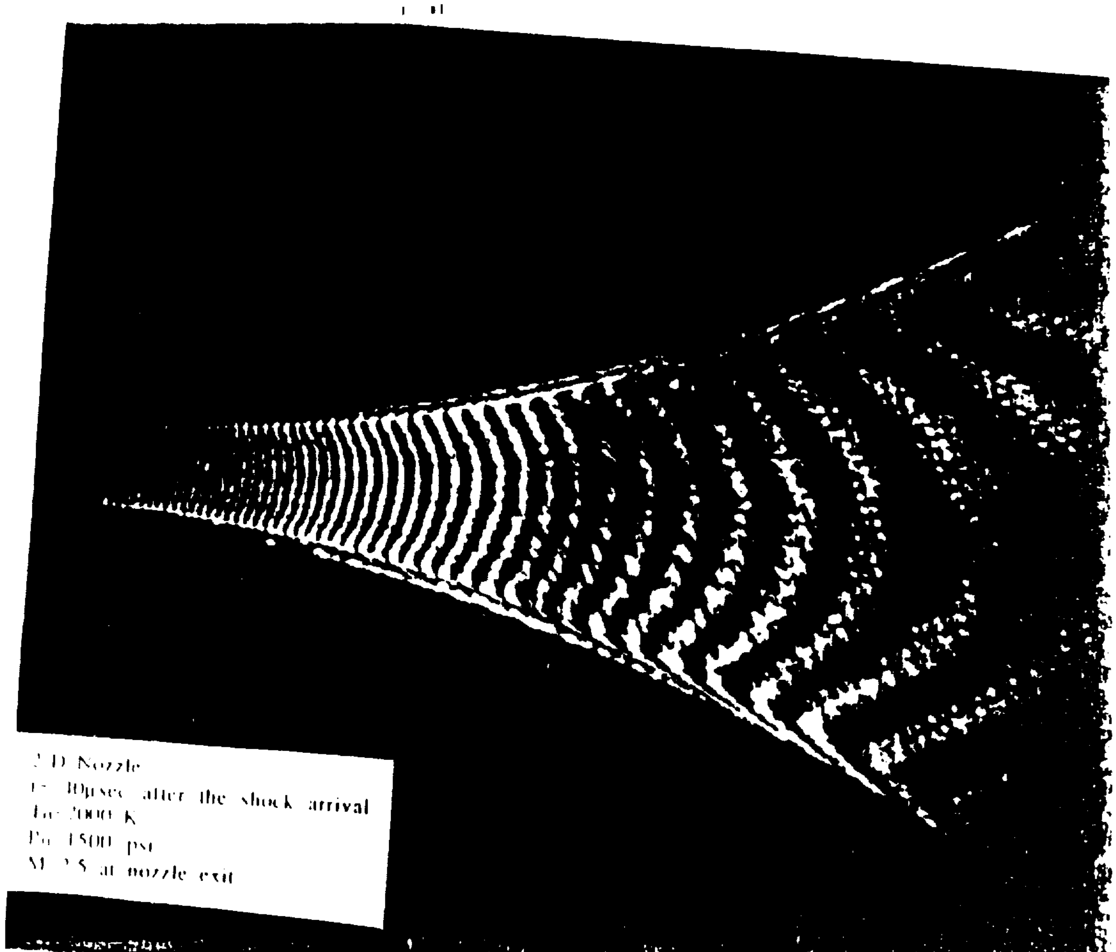
AT NASA AMES RESEARCH CENTER

TUBE, in	DRIVER GAS	DRIVER GAS	DRIVER
4	He	AIR	30 in.
24	He	AIR	30 in
4	H_2	H_2	54 in
4	H_2	H_2	CONICAL
4	He	Kr	54 in
4	He	H_2/Ne	54 in
4	H_2	AIR	CONICAL

TUBE, in	DRIVER GAS	DRIVER GAS	DRIVER
4	He	AIR	CONICAL
24	He	AIR	CONICAL
4	N_2	AIR	CONICAL
4	He	Ar	CONICAL
4	He	CO_2	CONICAL
4	He	AIR	54 in




Ames 10 cm Shock Tube Nozzle Flow
Translational and Vibrational Temp.,
Tt=7157K, pt=1493psi, α=4 7x10^8 cm^-1
Normalized Temperatures
x (cm)
T/Tt Landau-Teller
Tv/Tt Landau-Teller
T/Tt SSH-Master Eqn
Tv/Tt SSH-Master Eqn
0 90
0 85
0 80
0 75
0 70
0 65
0 60
0 55
0 50
0 45
0 40
0 35
0 30
0 25
0 20
0 0
1 0
2 0
3 0
4 0
5 0
6 0
7 0
8 0
9 0


2 D Nozzle
after the shock arrival
1500 psi
at nozzle exit

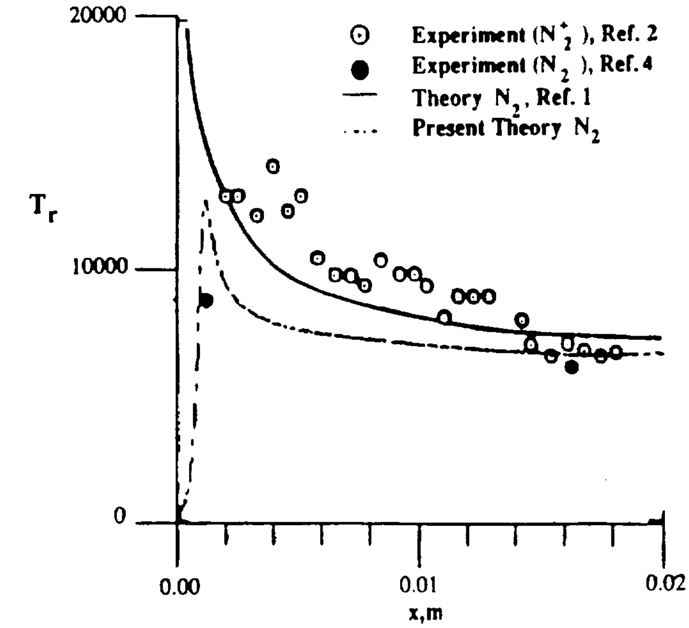


Figure 9. Comparison of theory and experiment, rotational temperature

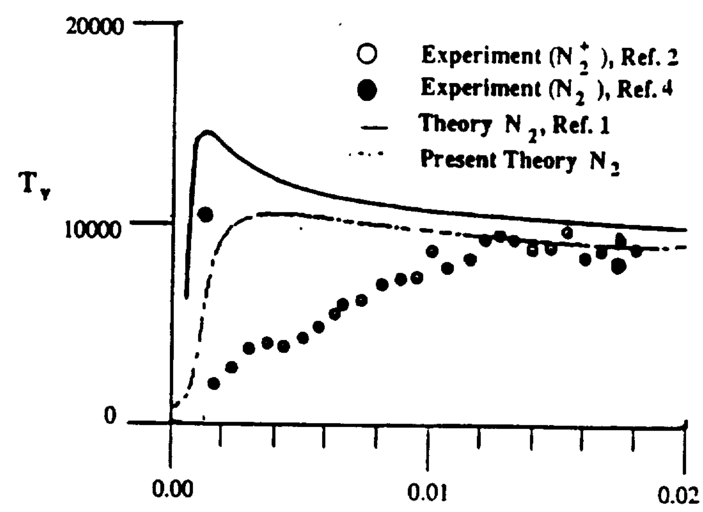


Figure 10. Comparison of theory and experiment, vibrational temperature

FLIGHT DATA ANALYSIS

TECHNOLOGY NEEDS

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

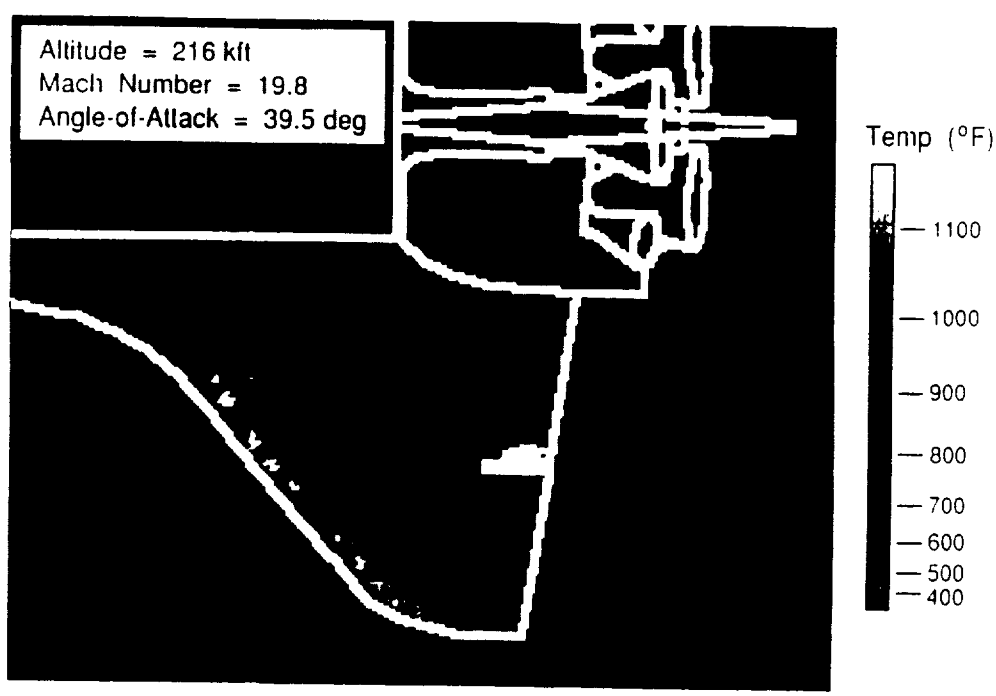
CURRENT PROGRAM S-O-A

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

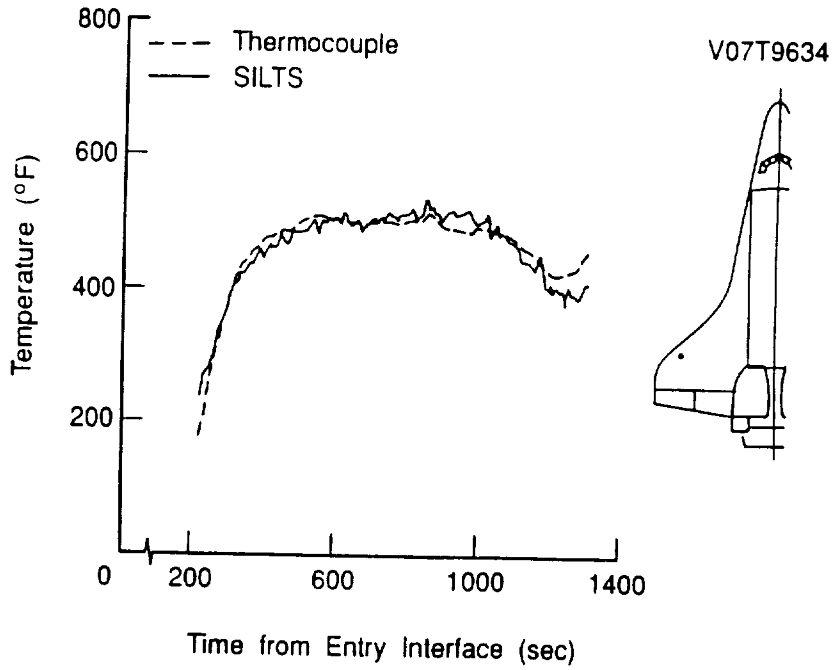
AUGMENTED PROGRAM

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

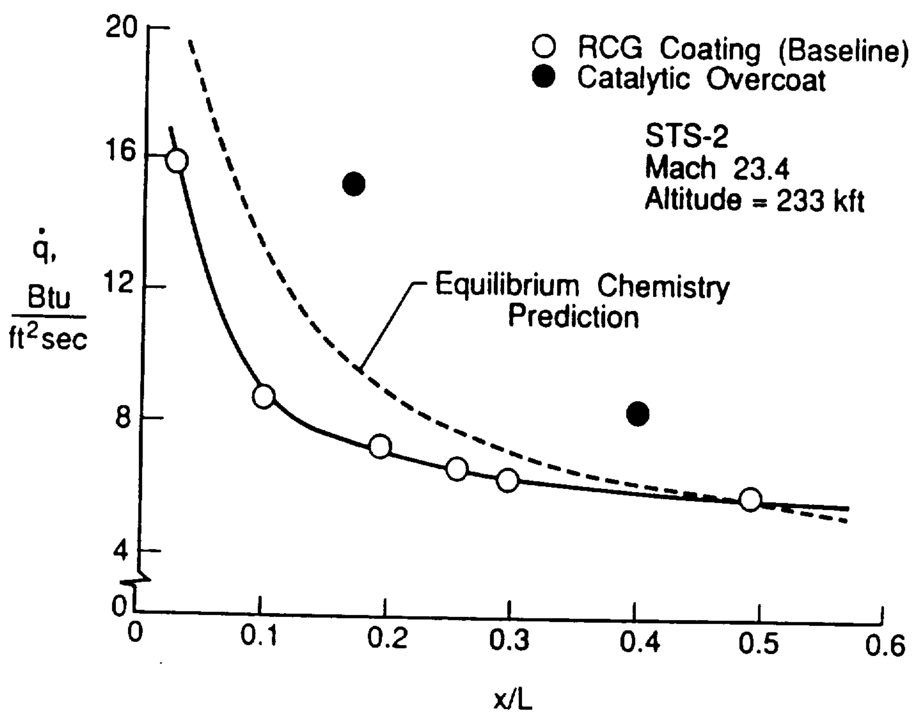
TYPICAL SILTS QUANTITATIVE DATA - STS-28



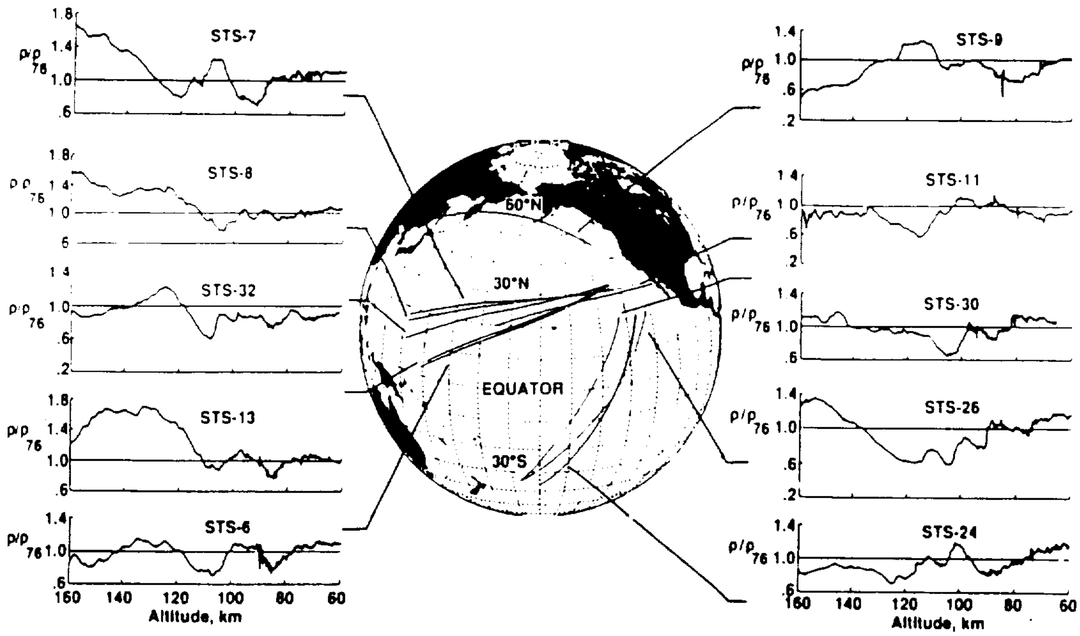
STS-28 SILTS - THERMOCOUPLE DATA COMPARISON



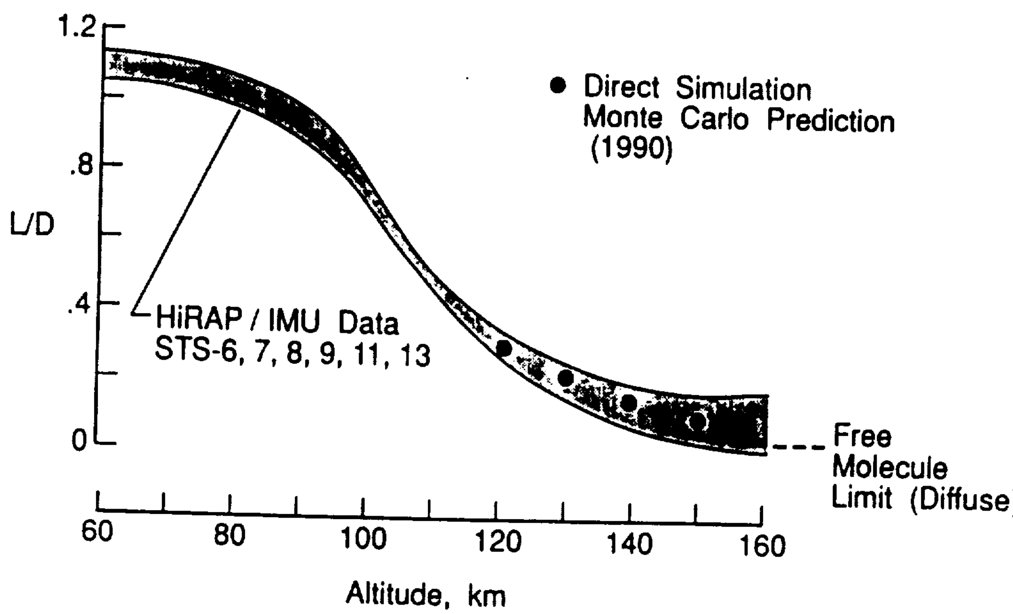
CSE EXPERIMENT CONFIRMS NON-CATALYTIC BENEFIT OF GLASS TILE COATING IN FLIGHT ENVIRONMENT



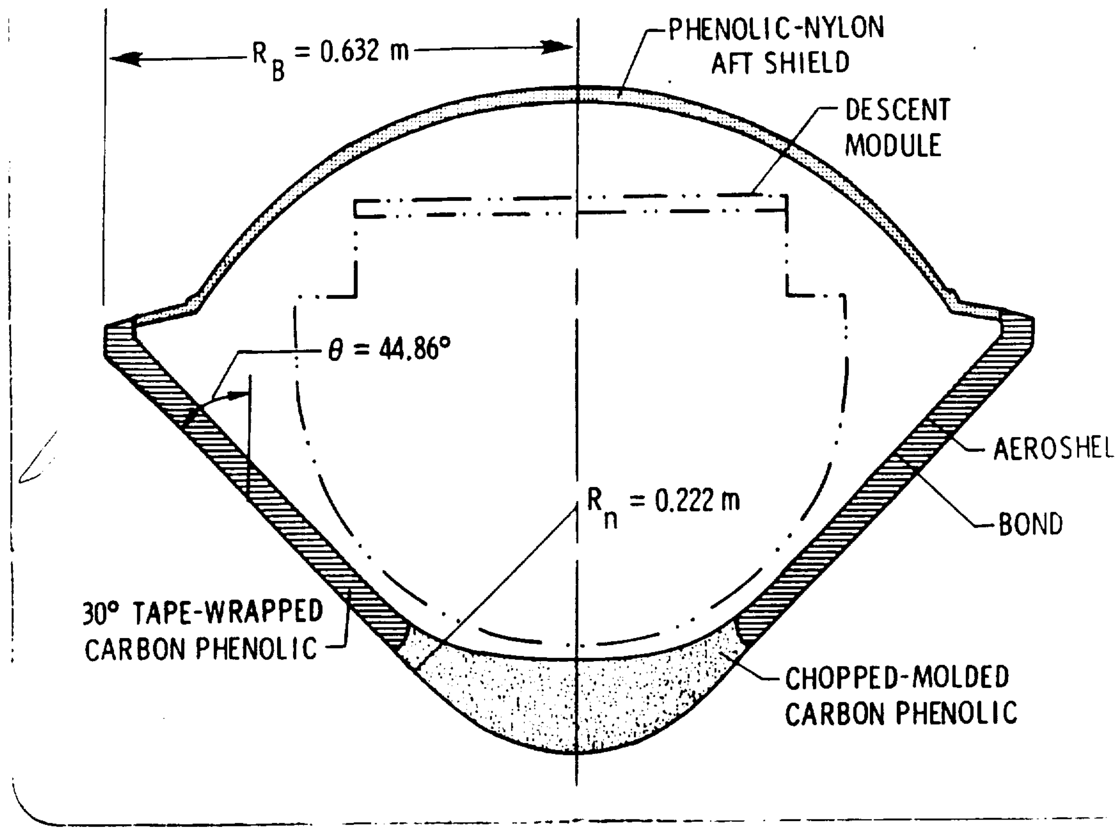
SHUTTLE ACCELEROMETRY (HiRAP/IMU) DENSITY MEASUREMENTS



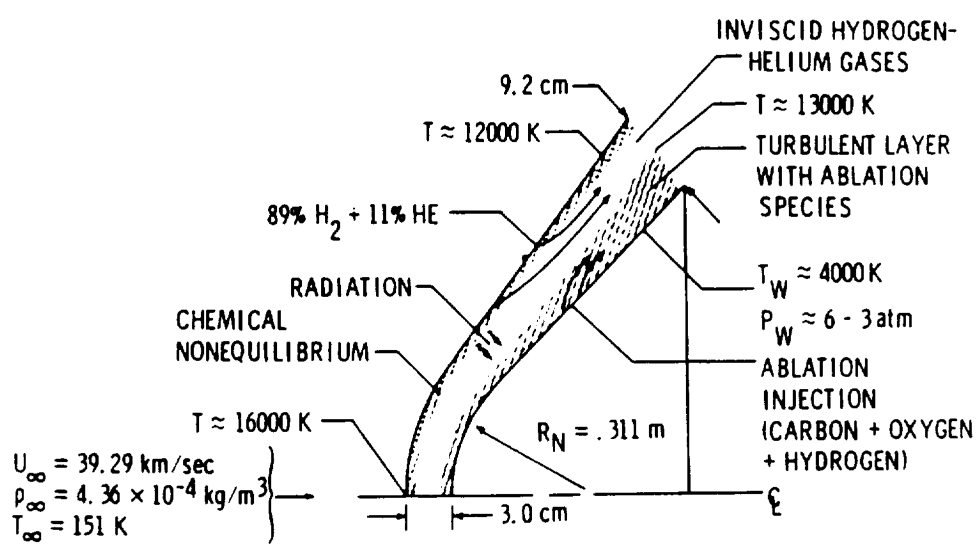
HiRAP PROVIDES VALIDATION DATA FOR RAREFIED FLOW COMPUTATIONAL TOOLS

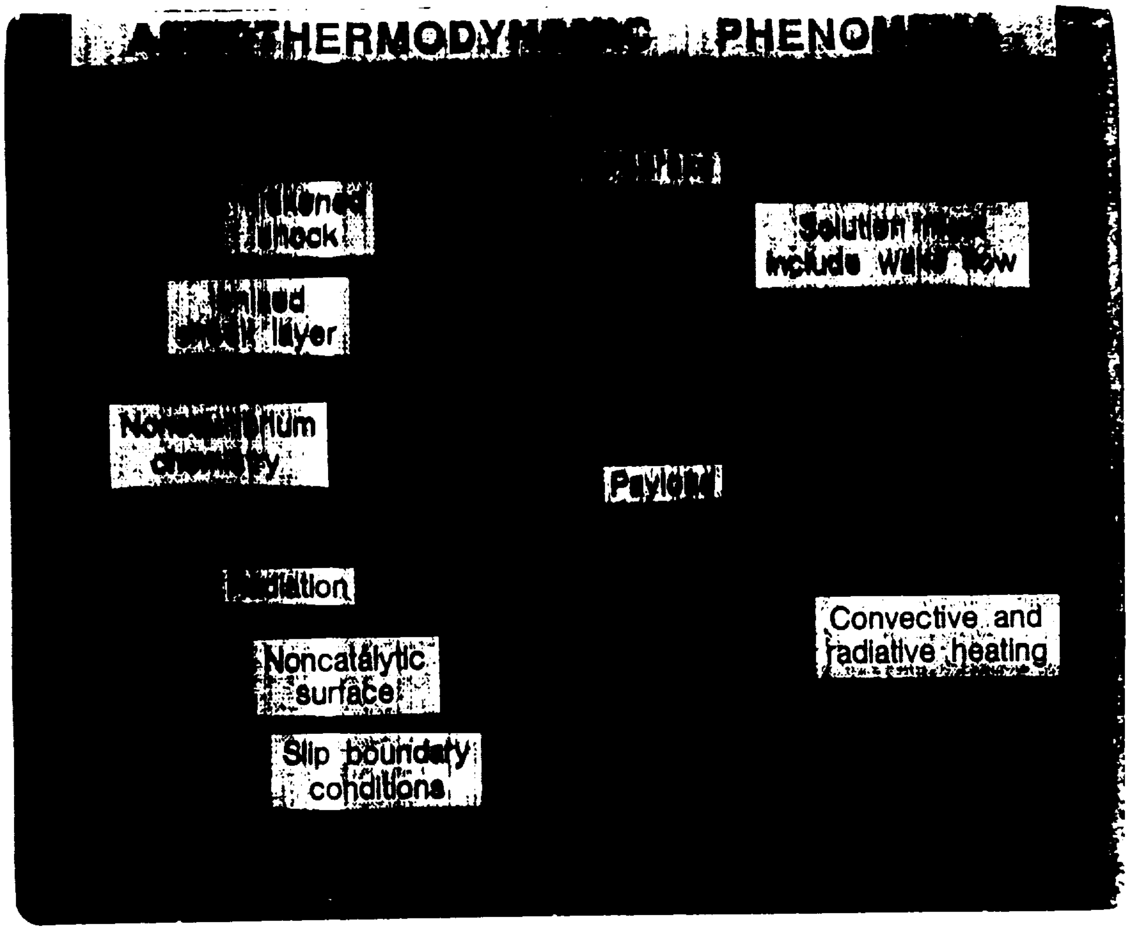


335-kg GALILEO ENTRY PROBE

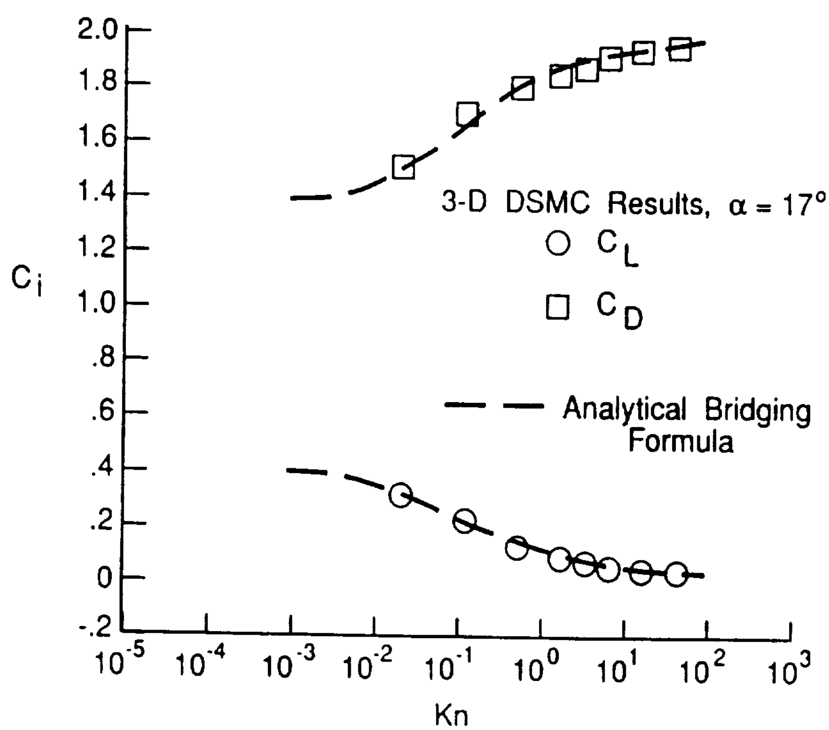


FOREBODY FLOW PHENOMENA–JUPITER ENTRY





DSMC PROVIDES DEFINITION OF AFE RAREFIED FLOW AERODYNAMIC PERFORMANCE



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EXPERIMENTAL RESEARCH/COMPUTATIONAL VALIDATION

	FY 93	FY 94	FY 95	FY 96	FY 97
GROUND-BASED DATA ACQUISITION AND ANALYSIS	▲ Complete Nonequilibrium Air Radiation Database	▲ Thermal Nonequilibrium Data for Free Jet		Δ Thermochemical Nonequilibrium Reactions and Radiation (Expanding CO_2 / N_2)	Δ Aerodynamic Database for Mars Aerocapture/Entry
FLIGHT DATA ANALYSIS		▲ Complete OARE Analysis	Δ Initiate Analysis of Galileo Data	Δ Initiate Analysis of AFE Data	

AEROTHERMODYNAMICS BASE R&T PROGRAM

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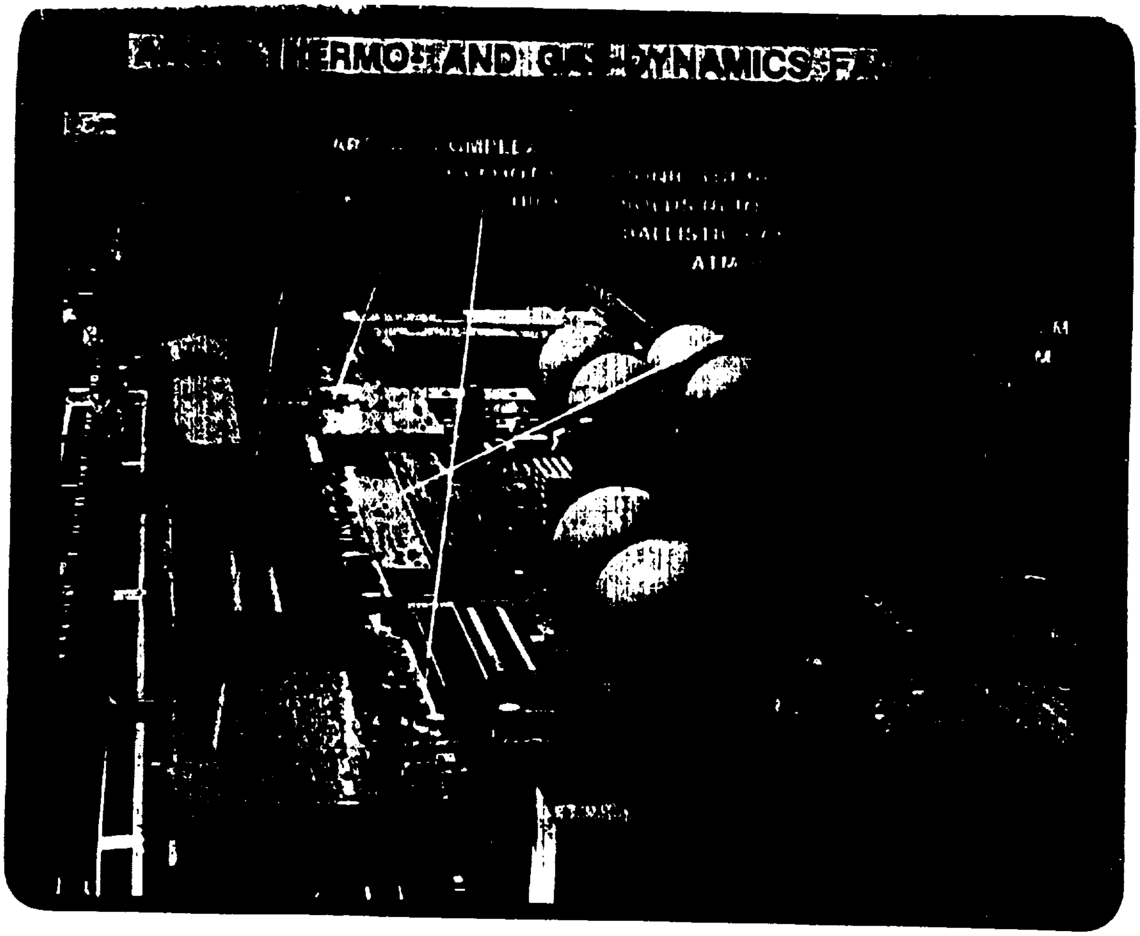
FACILITIES RESEARCH/ DEVELOPMENT



AEROTHERMODYNAMICS BASE R&T PROGRAM

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AMES FACILITIES

FACILITIES	IDEAL GAS			REAL GAS				RUN TIME
	M<6	M = 6-10	M>10	Vibration	Dissociation	Ionization	RARE-FIED	Seconds
3.5 '	X	X	X					10^{2}
16 "	X	X	X	X	X			10^{-2}
EAST	X	X	X	X	X	X		10^{-3}
Arc-Jet	X			X	X	X		
Ballistic Range	X	X	X	X	X	X		10^{-7}
UC Berkeley	X	X	X	X			X	Cont.

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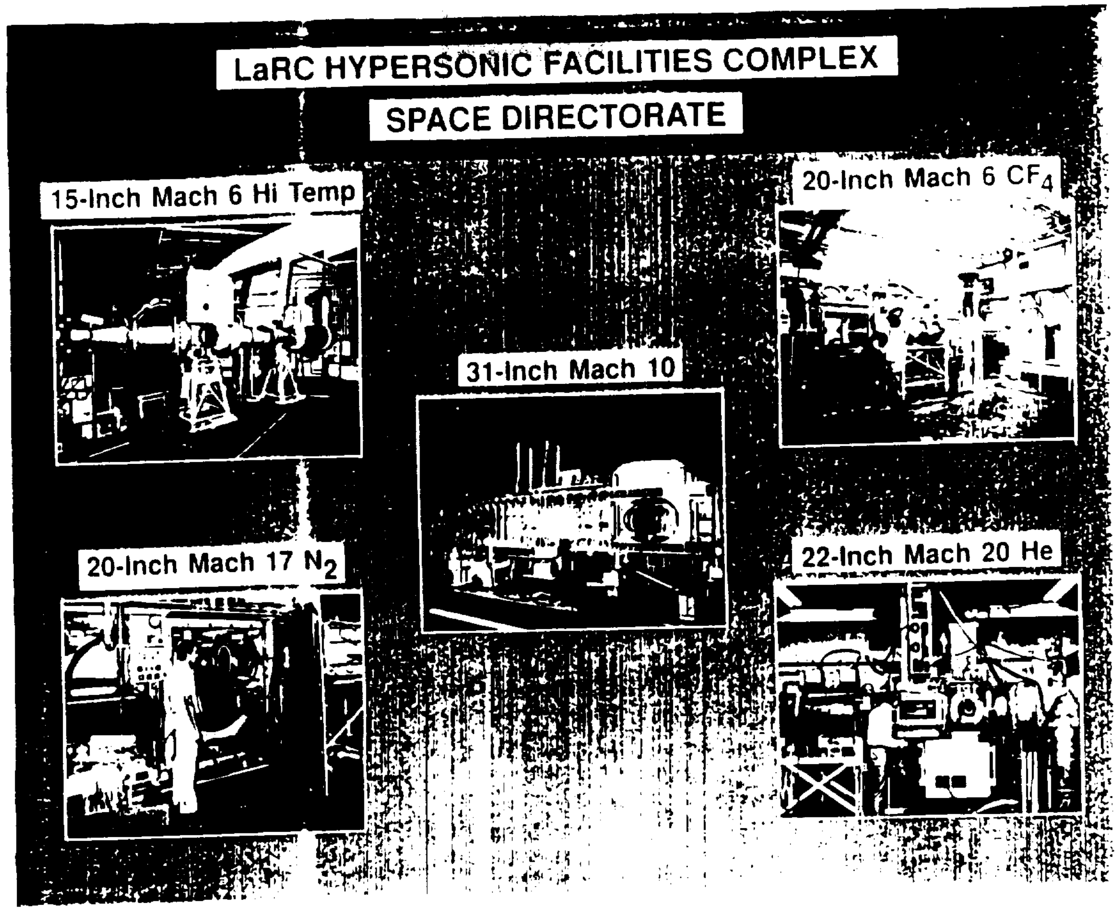

CHARACTERISTICS OF LaRC HYPERSONIC FACILITIES COMPLEX

Facility	Test Gas	p_0, psia	To, °R	M_∞	R_∞/ft x 10^{-6}	$\frac{\rho_2}{\rho_\infty}$	Nozzle Type	Nozzle Exit, in.	Test Core, in.	Run Time, sec
20-In. M6 CF_4	CF_4	100-2500	1100-1460	6	0.03-0.7	12.0	Axis.	20 D.	14	10-30
20-In. M6	Air	30-500	760-960	6	0.5-9	5.3	2D	20x20	12x12-14x14	120-900
15-In. M6 Hi T	Air	50-250	1100-1500	6	0.5-4	5.3	Axis.	15 D.	8-10	120
12-In. M6 Hi P	Air	50-2700	700-1060	6	1-40	5.3	Axis.	12 D.	4-8	180 to vacuum 900 to atm
18-In. M8	Air	30-3000	1160-1500	7.5-8.0	0.1-12	5.6	Axis.	18 D.	7-16	90 to vacuum 600 to atm
31-In. M10	Air	125-1450	1830	10	0.25-2	6.0	3D	31x31	12x12-14x14	60
20-In. M17 N_2	N_2	2000-5500	2800-3500	17	0.2-0.8	6.6	Axis.	20 D.	8-10	3600
60-In. M18 He	He	300-2000	520	16.5-18.5	2-15	4	Axis.	60 D.	20	5
22-In. M20 He	He	300-3000	520-1000	18-22	1-20	4.0	Axis.	22 D.	8-10	20-40

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EXISTING FACILITY UPGRADES

TECHNOLOGY NEEDS

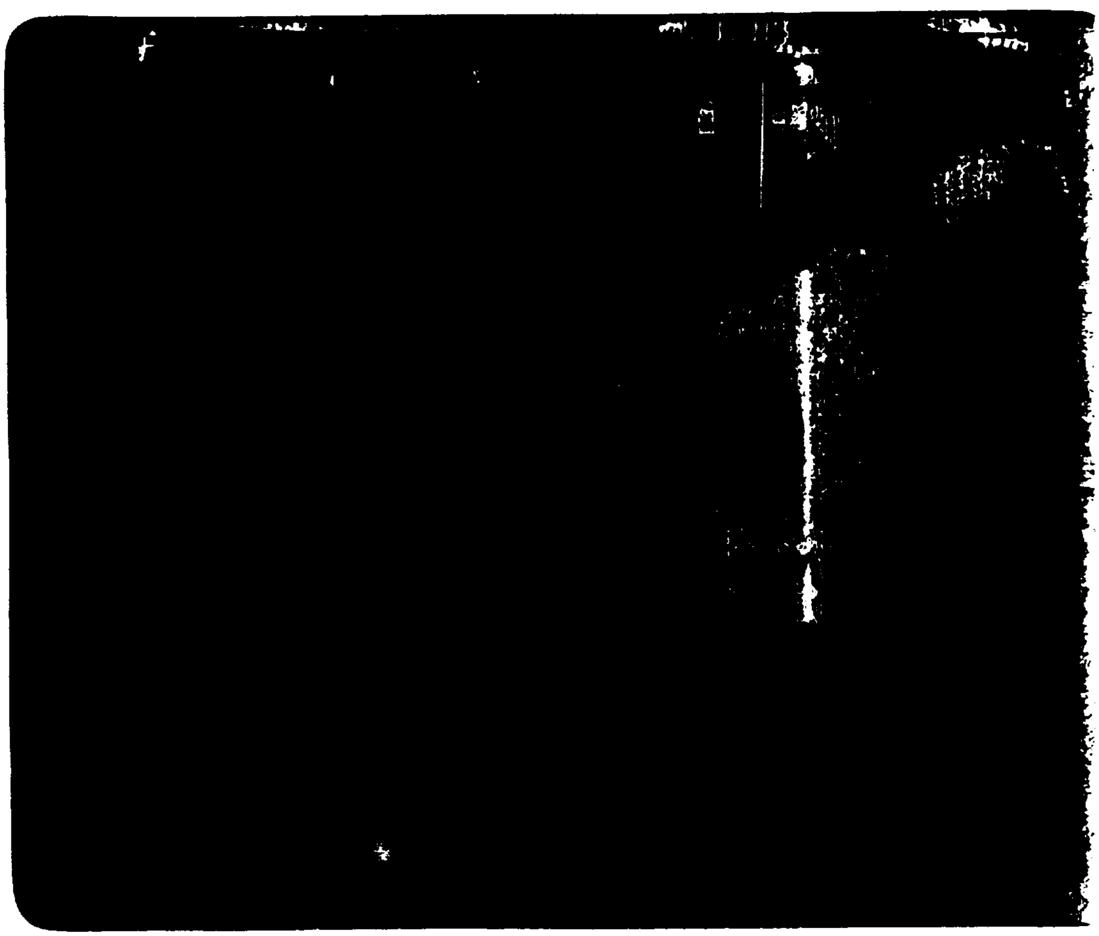
HIGH FLOW QUALITY, EXPANDED SIMULATION BOUNDARIES, INCREASED OPERATIONS EFFICIENCY AND PRODUCTIVITY

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

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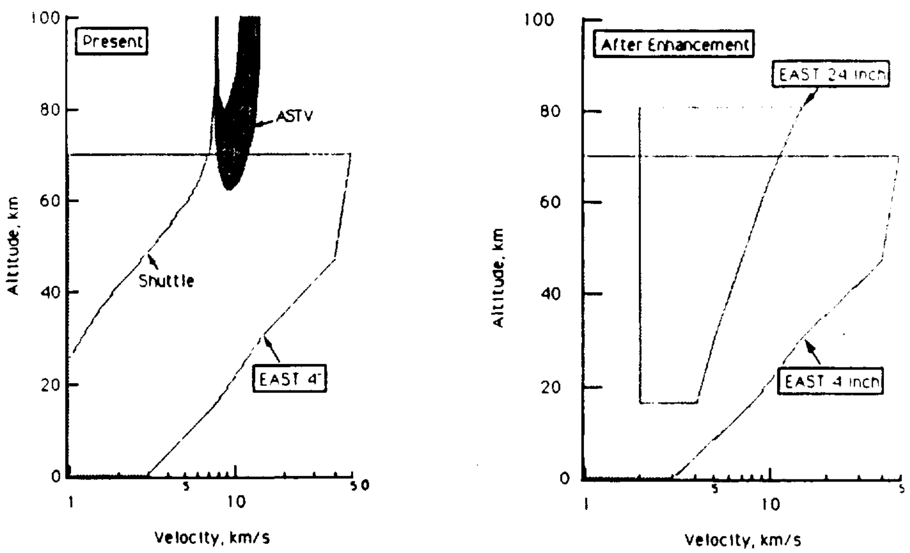
Shock Wave Generation Capabilities for Shock Structure Studies



AEROTHERMODYNAMICS BASE R&T PROGRAM

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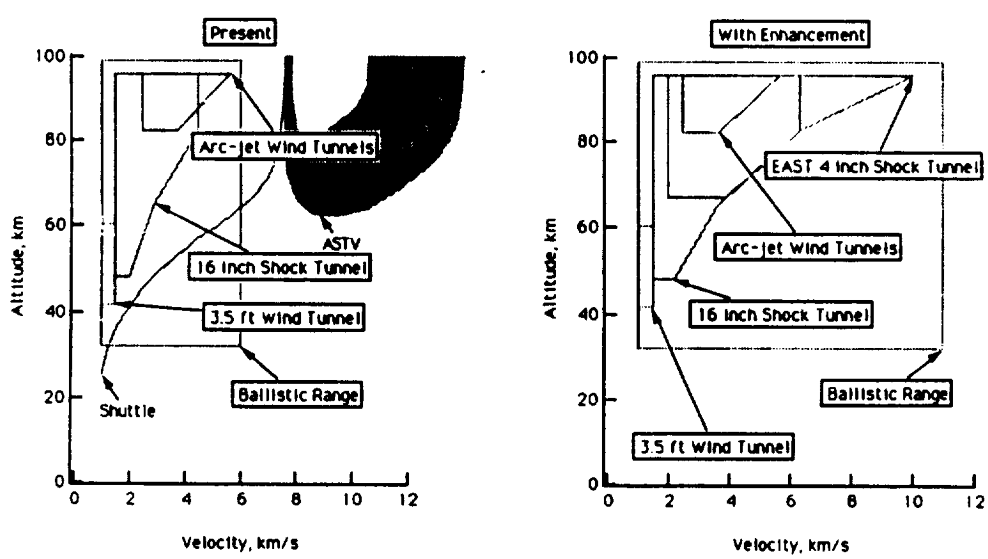
SIMULATING CAPABILITIES FOR 1/100 SCALE MODEL SIMULATING ENTHALPY, MACH, AND REYNOLDS NUMBERS



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

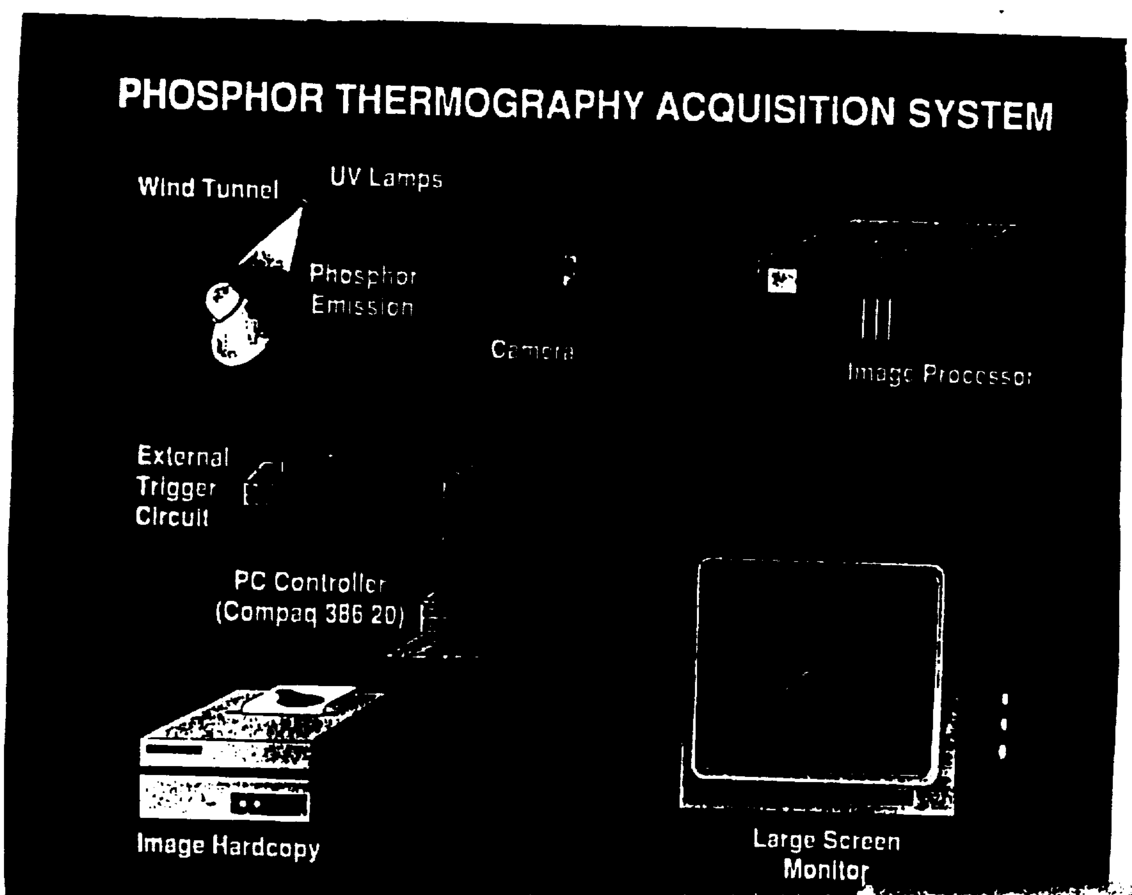
CURRENT PROGRAM S-O-A

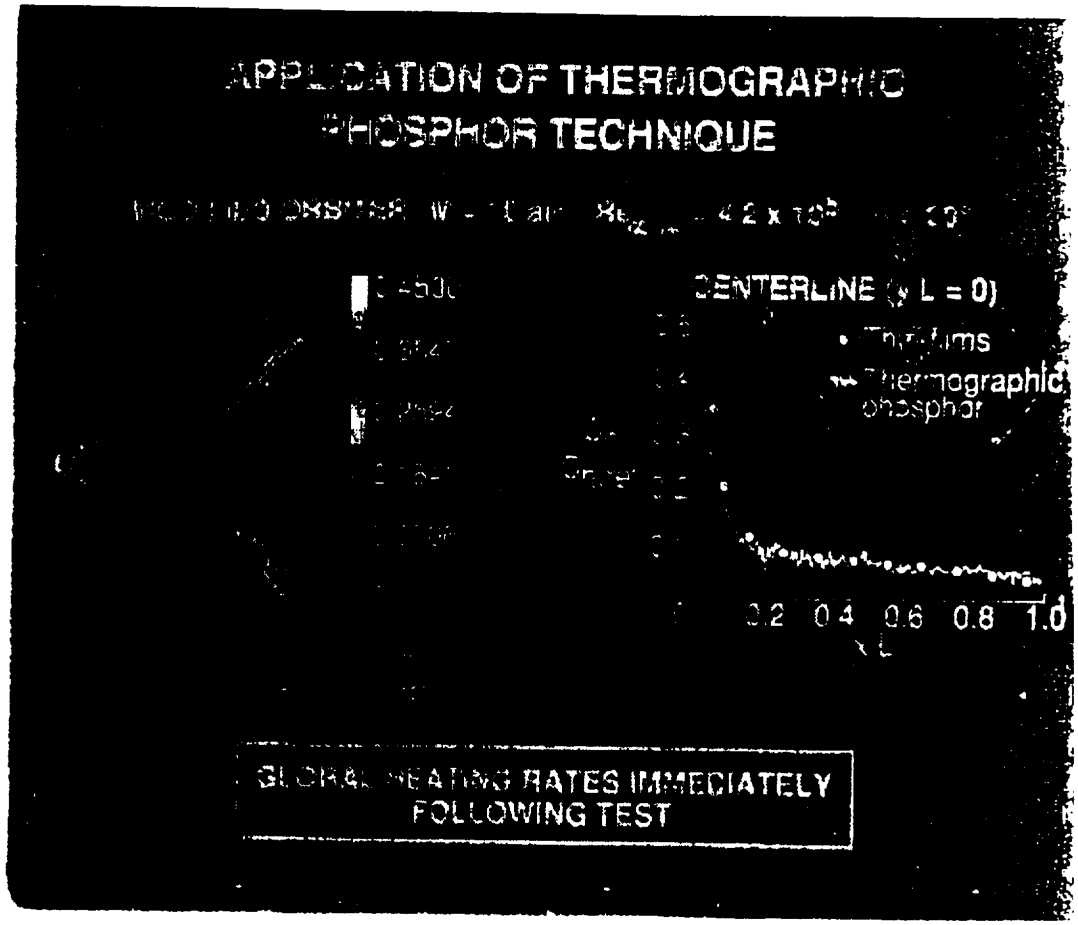
REFINEMENT OF GLOBAL SURFACE TEMPERATURE MEASUREMENTS, LIMITED APPLICATION OF NONINTRUSIVE MEASUREMENT TECHNIQUES (SCATTERING AND LASER VELOCIMETRY IN MACH 6 AIR AND 3.5'; OMA EMISSION SPECTRA, RAMAN SCATTERING, AND LHI IN EAST FACILITY; SCANNING LASER ABSORPTION AND LHI IN 16" SHOCK TUNNEL), LIMITED 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 O_2 LASER TOMOGRAPHIC), DEVELOP FLOW VISUALIZATION SYSTEMS WITH VIDEO RECORDING AND IMAGE ENHANCEMENT, OBTAIN FAST RESPONSE INSTRUMENTATION

L-91-3920





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

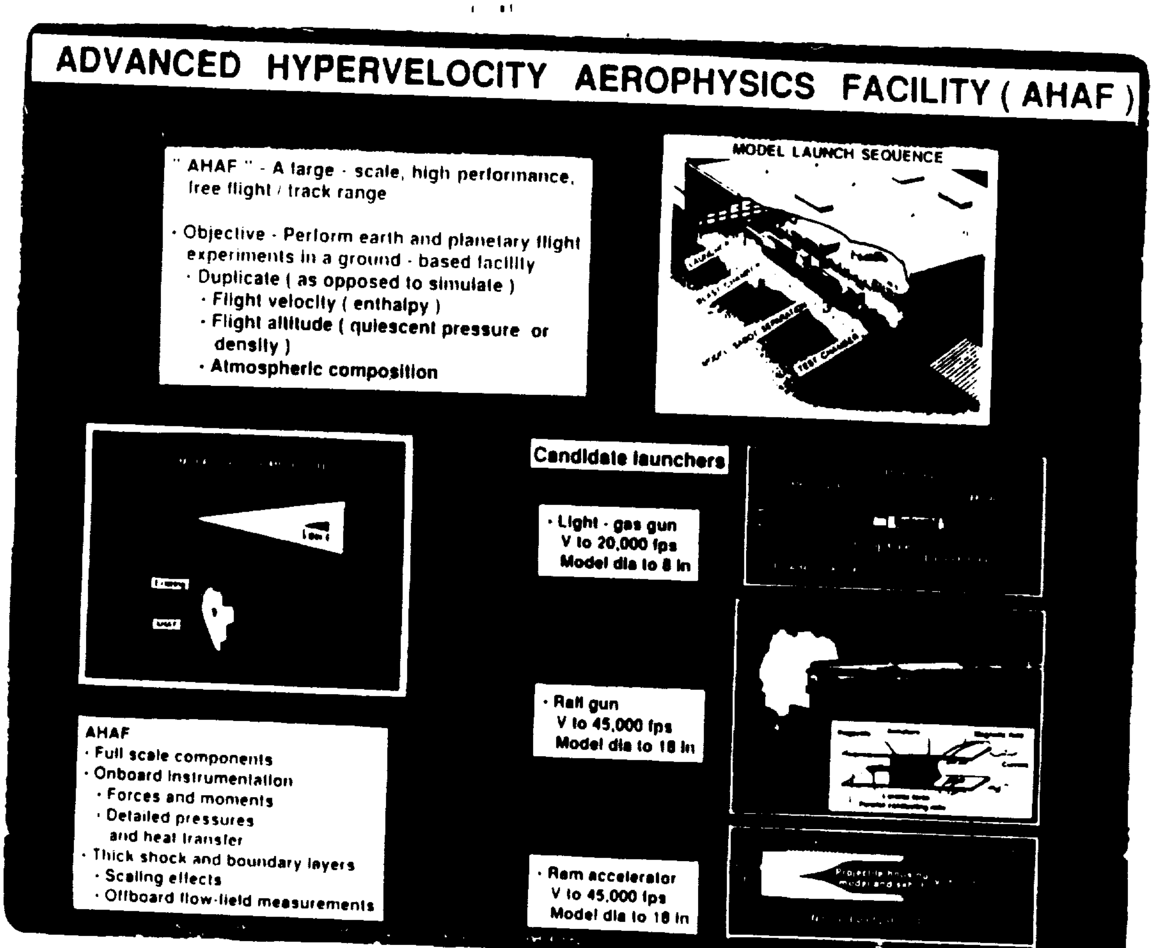
WHAT IS DIFFERENT ABOUT ADVANCED HYPERVELOCITY AEROPHYSICS FACILITY (AHAF)?

- In one word - SIZE

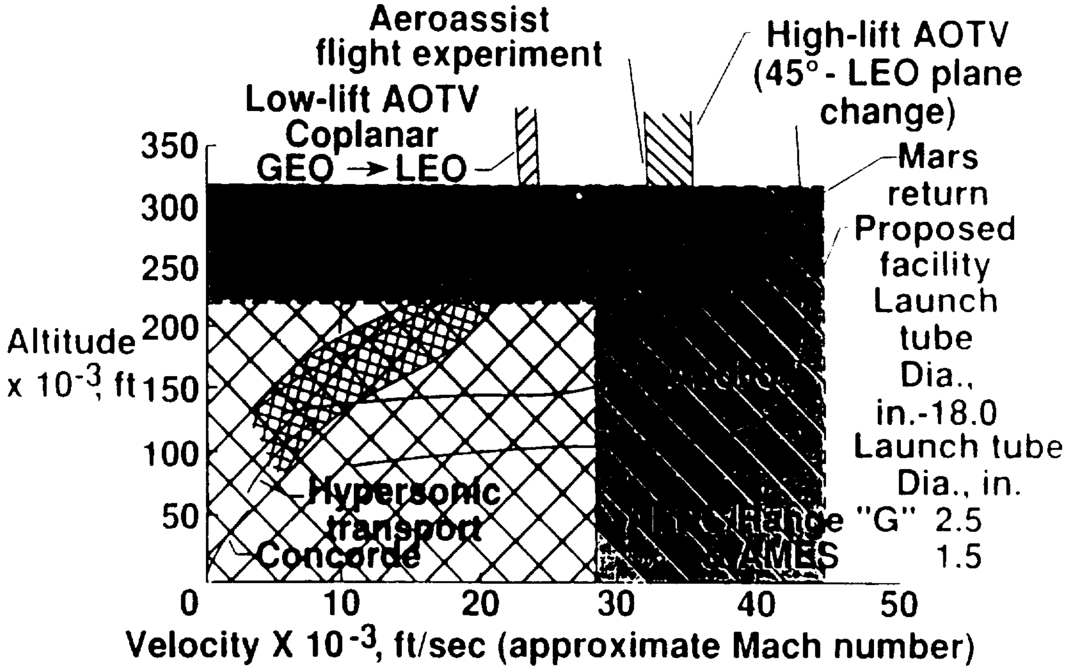
- Near order of magnitude increased in model size provides:
  - Testing of full-size vehicle components (e.g. nose tips)
  - Volume for large amounts of onboard instrumentation
    - Aerodynamic forces and moments
    - Detailed pressure and heat transfer distributions for analysis of aerodynamic and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

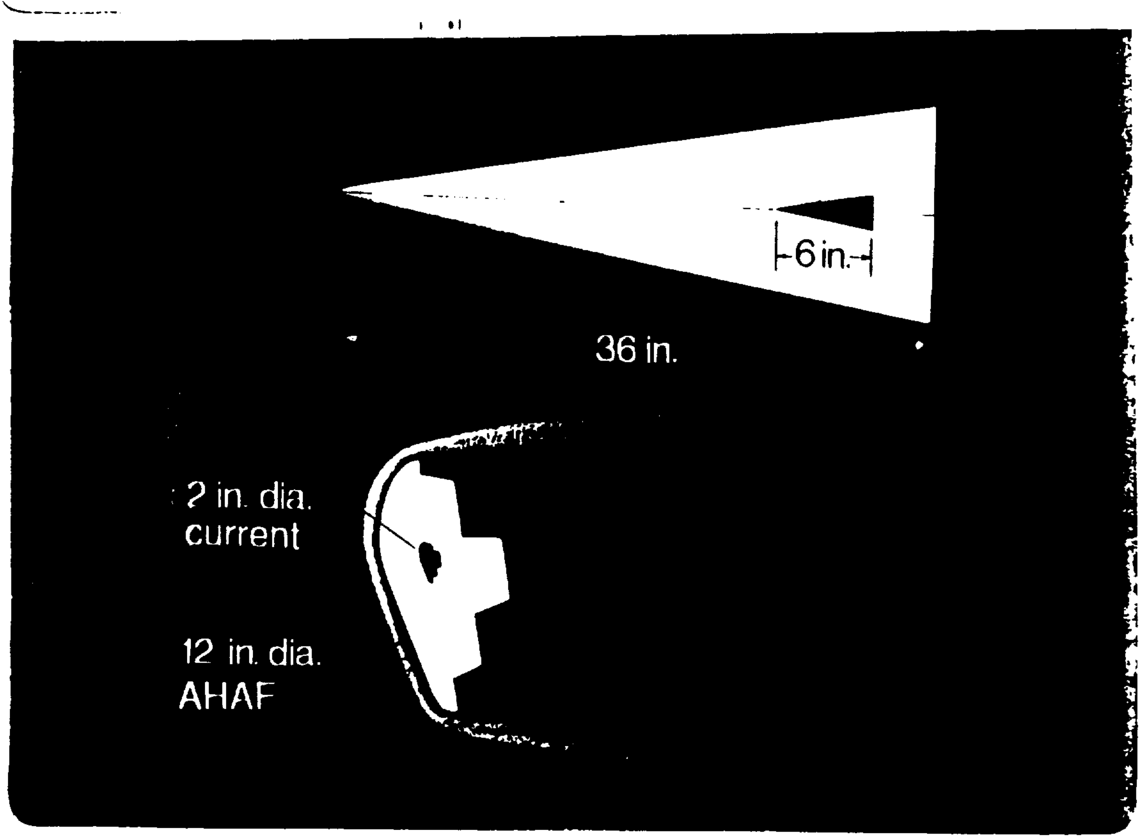
- Sufficient shock/boundary layer thickness for:
    - Determination of scaling (finite rate chemistry) effects
    - Measurement of flowfield properties via offboard advanced diagnostics

- Etc. (reference workshop proceedings NASA CP 10031)



COMPARISON OF VEHICLE FLIGHT REGIMES IN EARTH'S ATMOSPHERE





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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

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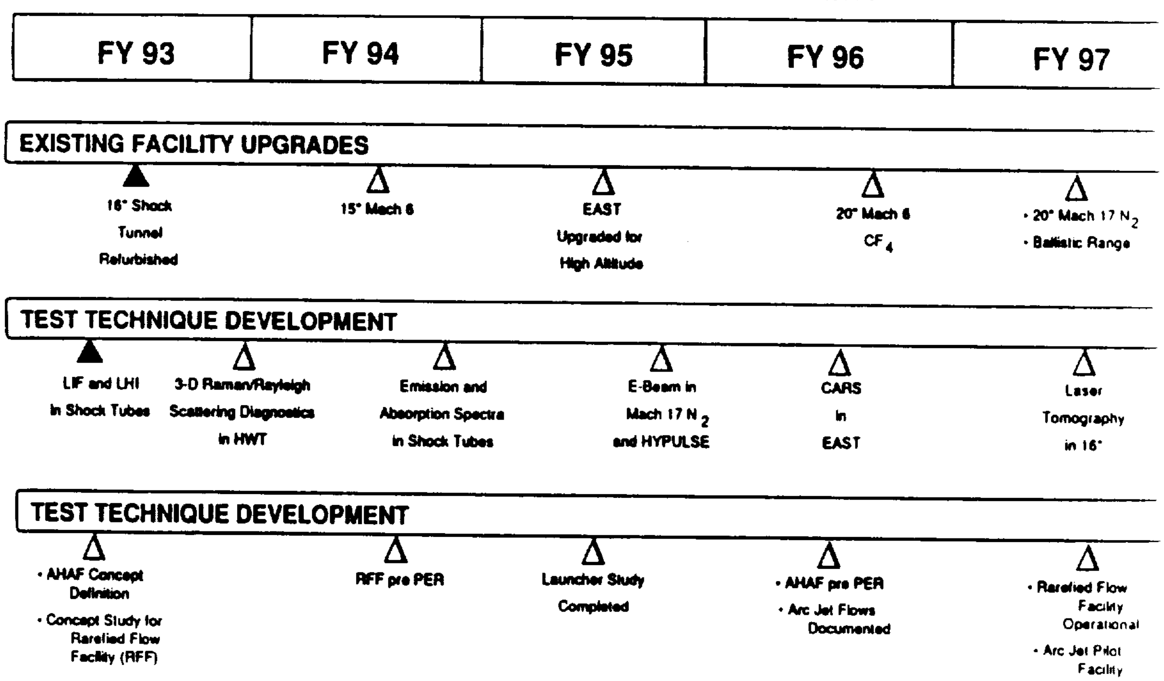
FACILITIES RESEARCH/DEVELOPMENT



CONFIGURATION ASSESSMENT

AEROTHERMODYNAMICS BASE R&T PROGRAM

CONFIGURATION ASSESSMENT

TECHNC. ..Y NEEDS

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

CURRENT PROGRAM S-O-A

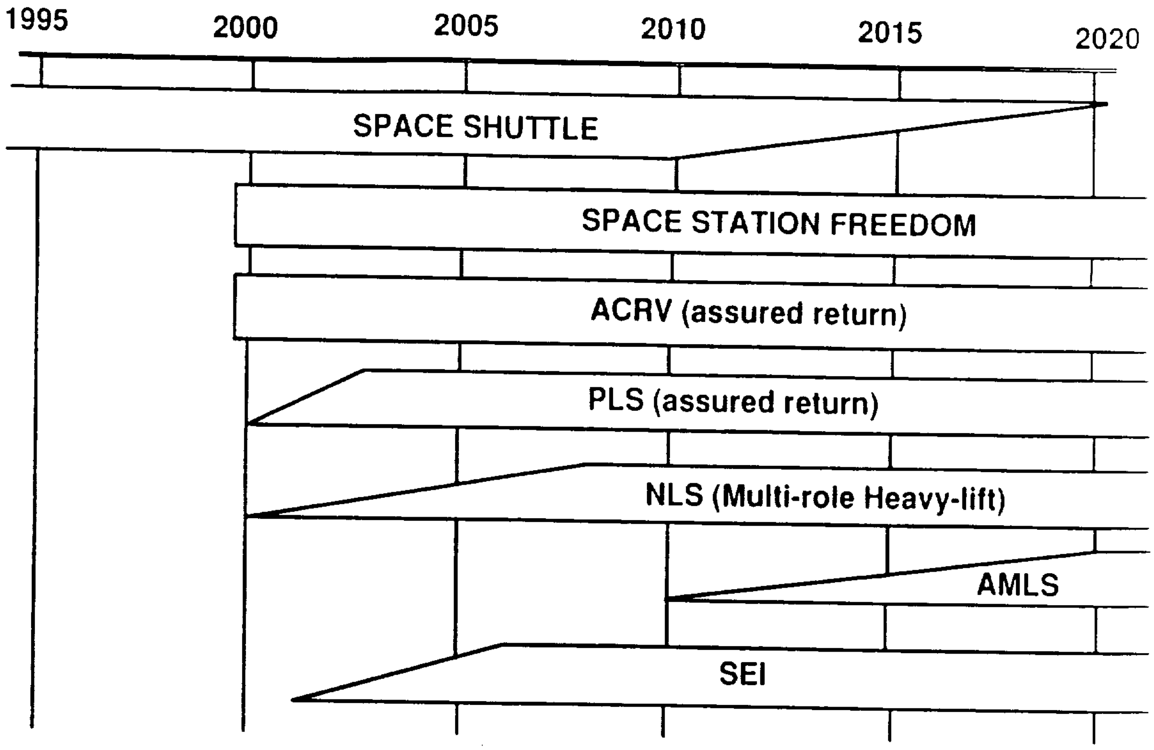
LIMITED RESOURCES ——► 1 - 2 VEHICLES AT A TIME
FOCUS ON ONE PLS CONCEPT AND AFE

AUGMENTED PROGRAM

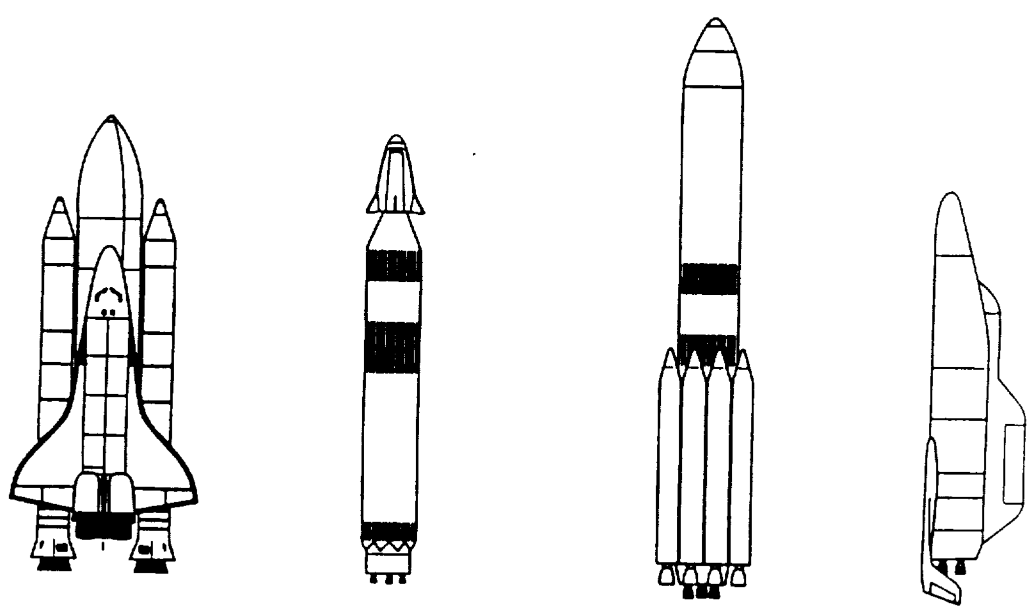
MODELS, COMPUTER TIME, AND FACILITY OPERATIONS TO ASSESS:

Mission	Config.	Mission	Config.
ACRV	(4 - 8)	SDIO-SSTO	(1 - 2)
PLS	(3)	NLS	(TBD)
AMLS	(Unlimited)	NDV	(TBD)
		OTHER	(TBD)

SPACE TRANSPORTATION ARCHITECTURE OPTIONS



SPACE TRANSPORTATION ARCHITECTURE SYSTEMS

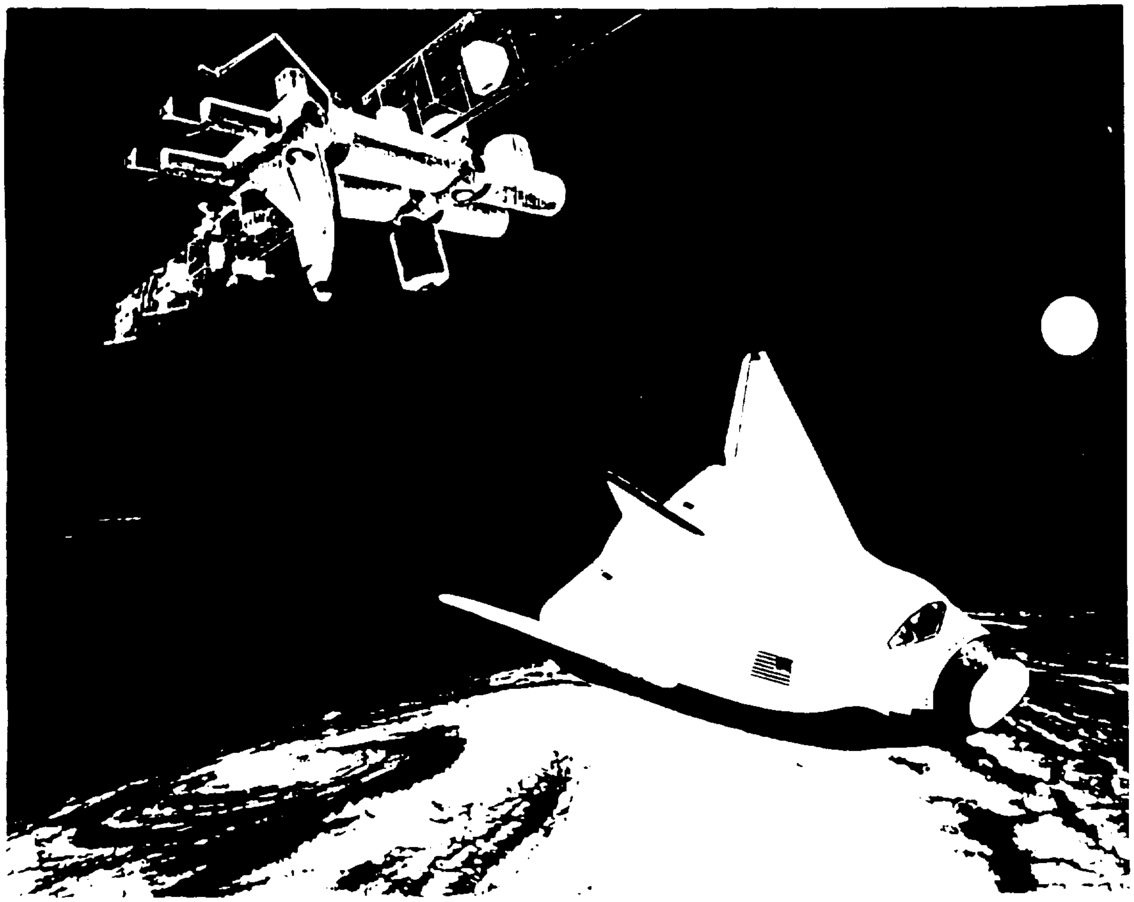


Space Shuttle

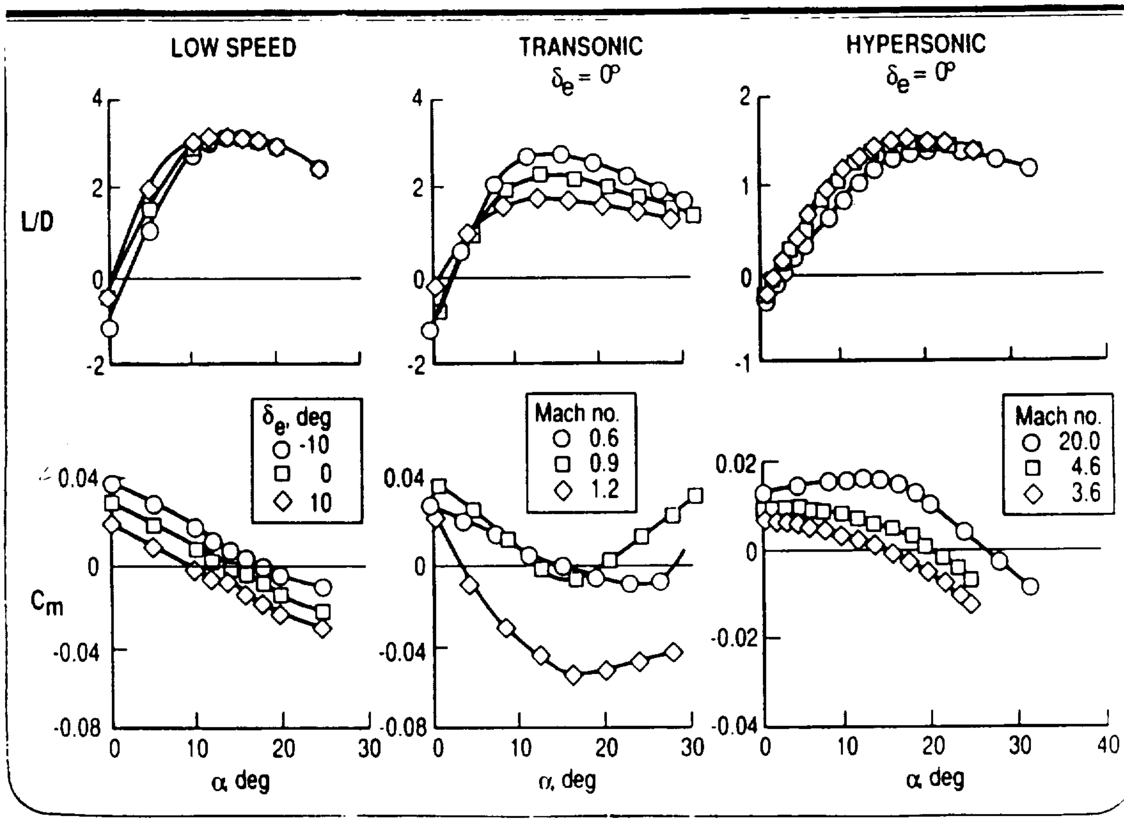
PLS NLS Core

NLS HEAVY LIFT Core+strapons

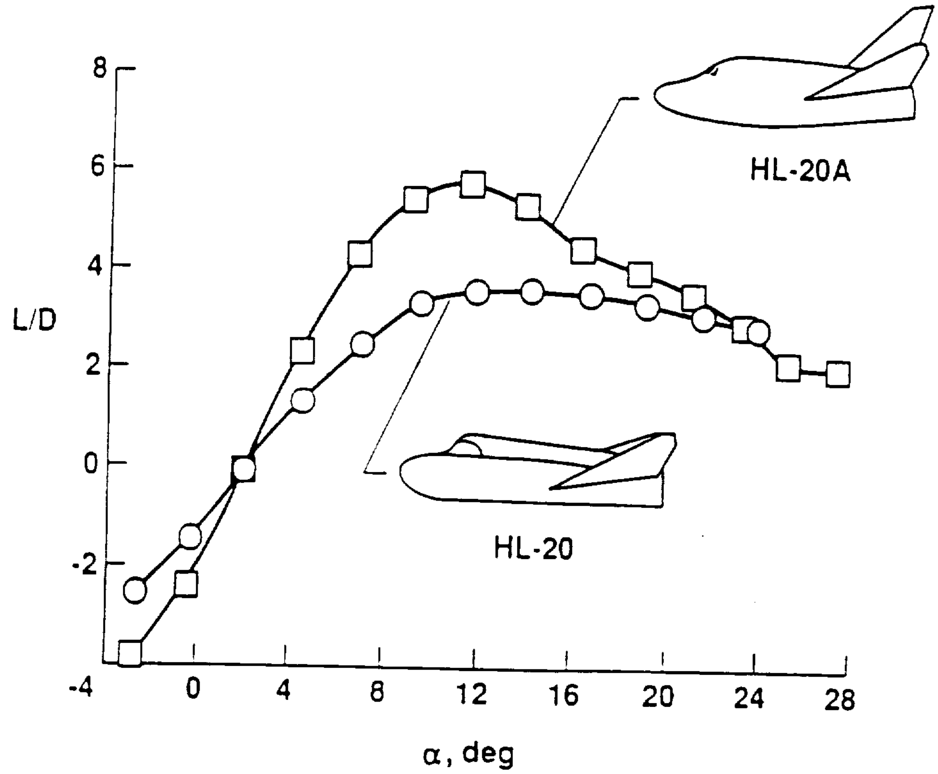
AMLS SSTO



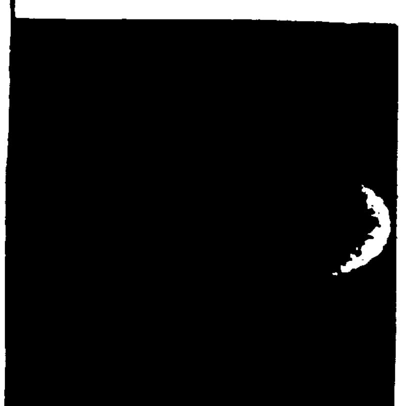
HL-20 LONGITUDINAL CHARACTERISTICS
(Moment ref = 0.54L)

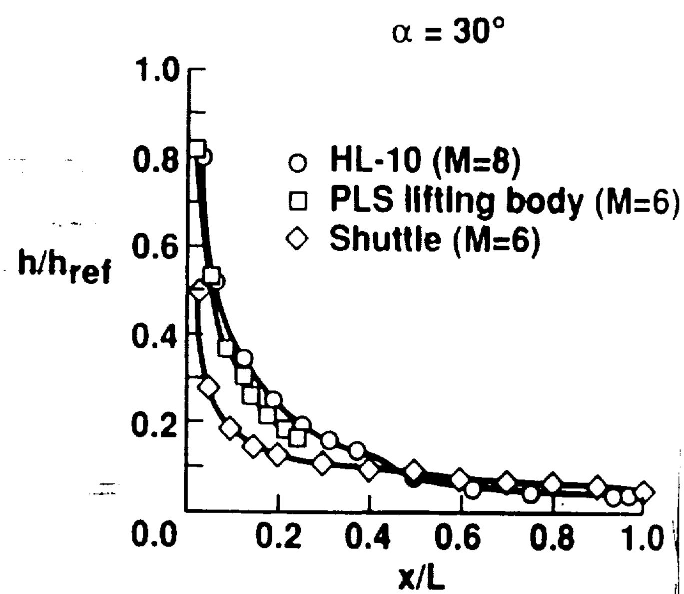


SUBSONIC L/D ENHANCEMENT FOR HL-20/HL-20A



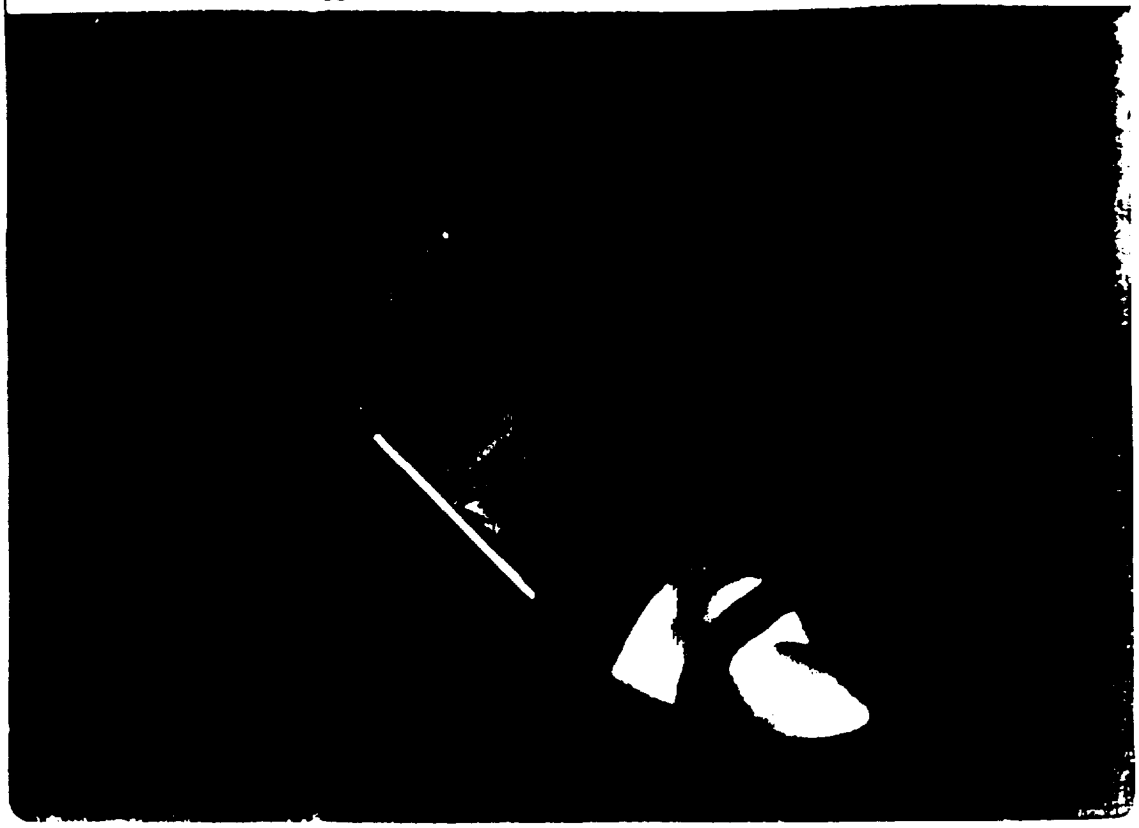
CHARACTERISTICS

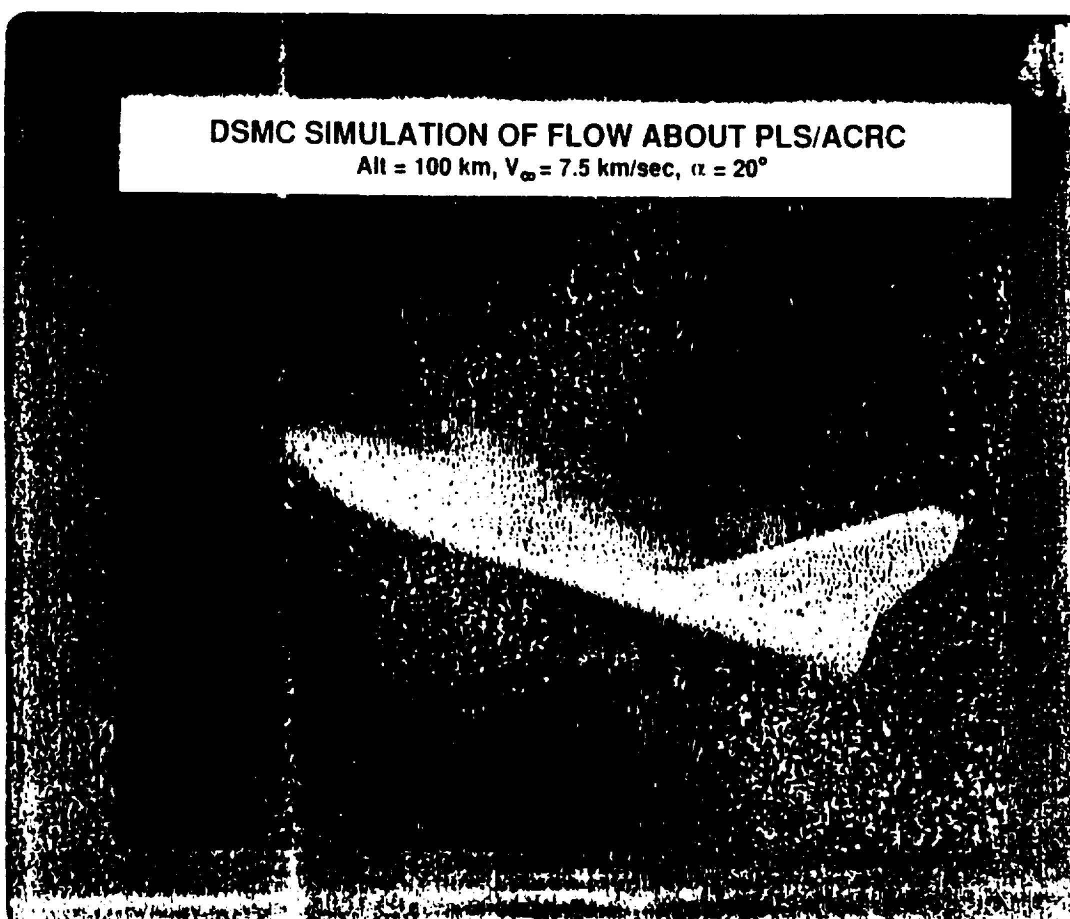




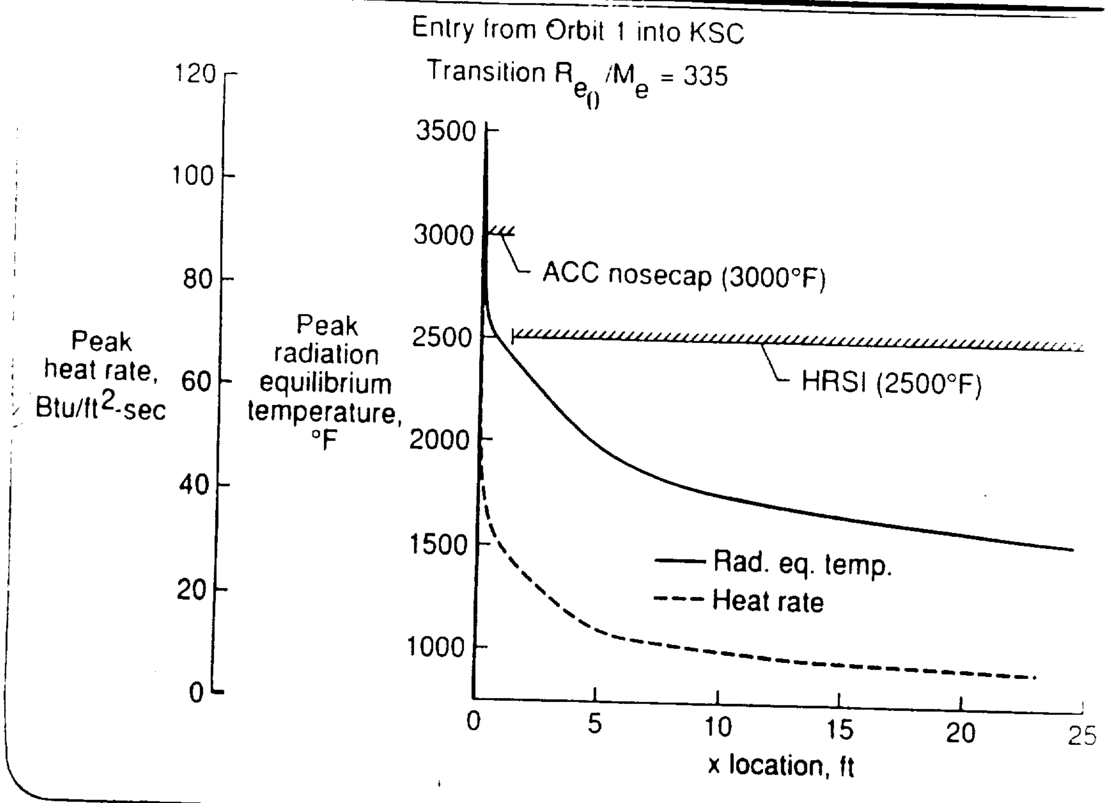
MACH NUMBER CONTOUR PLOTS

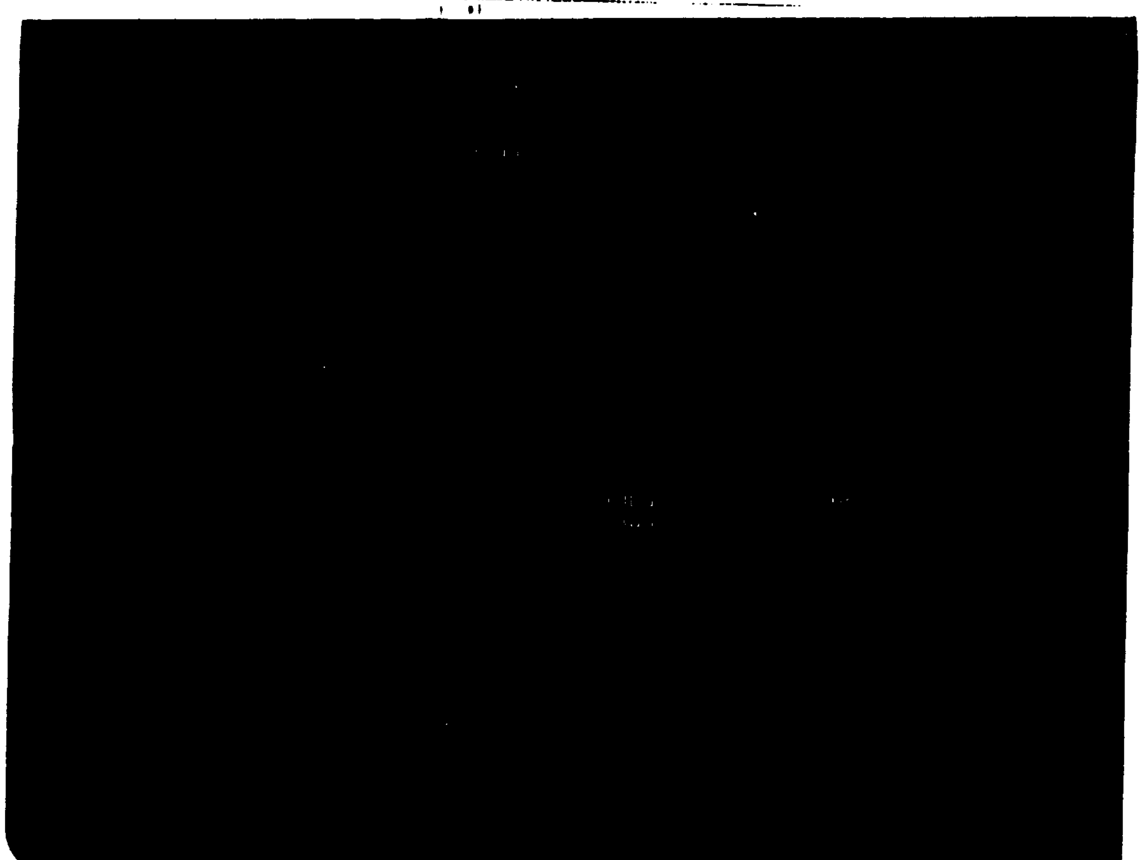
$M_{\infty} = 10 \quad \alpha = 25^{\circ} \quad \gamma = 1.4$



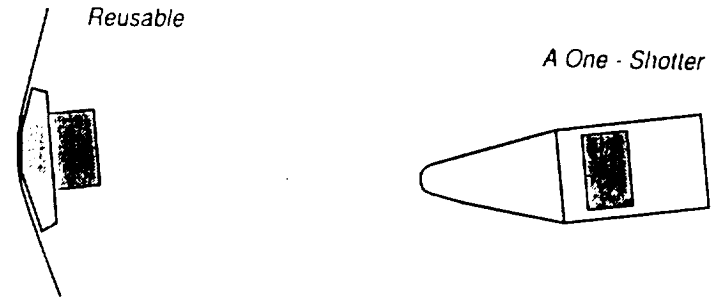


PLS WINDWARD CENTERLINE PEAK HEATING DISTRIBUTION/MATERIAL REQUIREMENTS





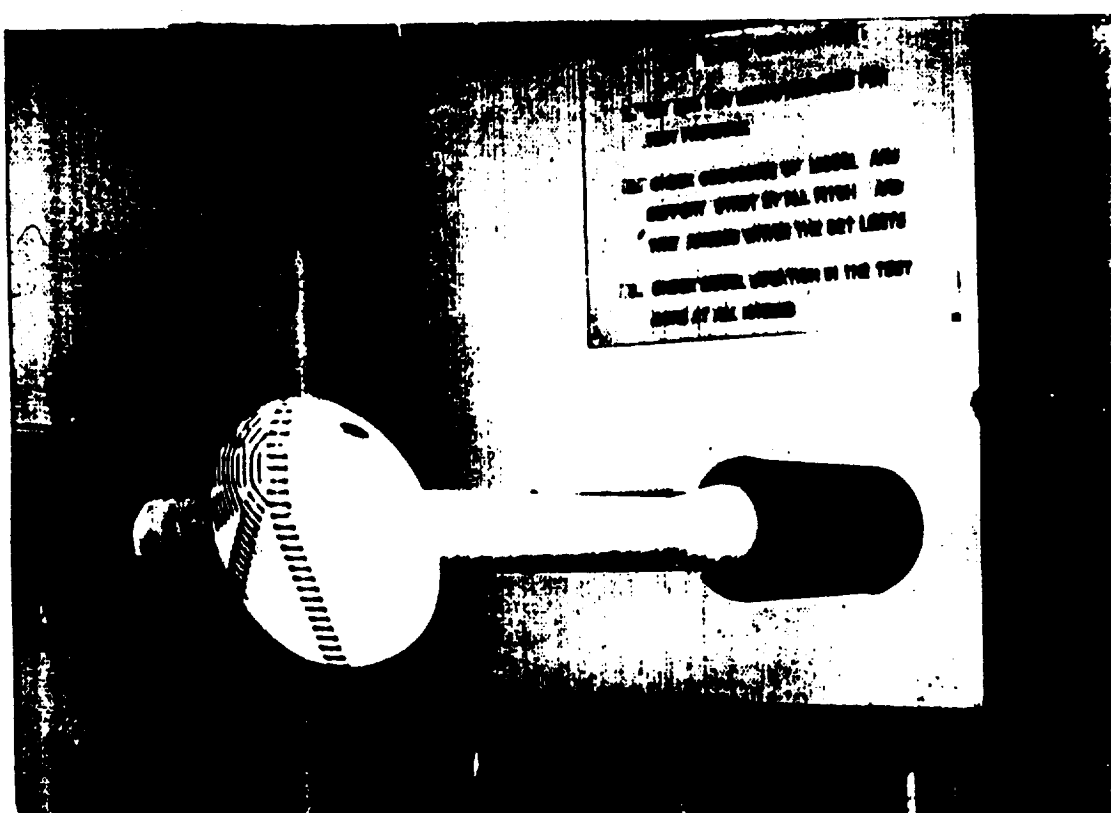
AEROASSIST VEHICLE DESIGN CHOICES



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

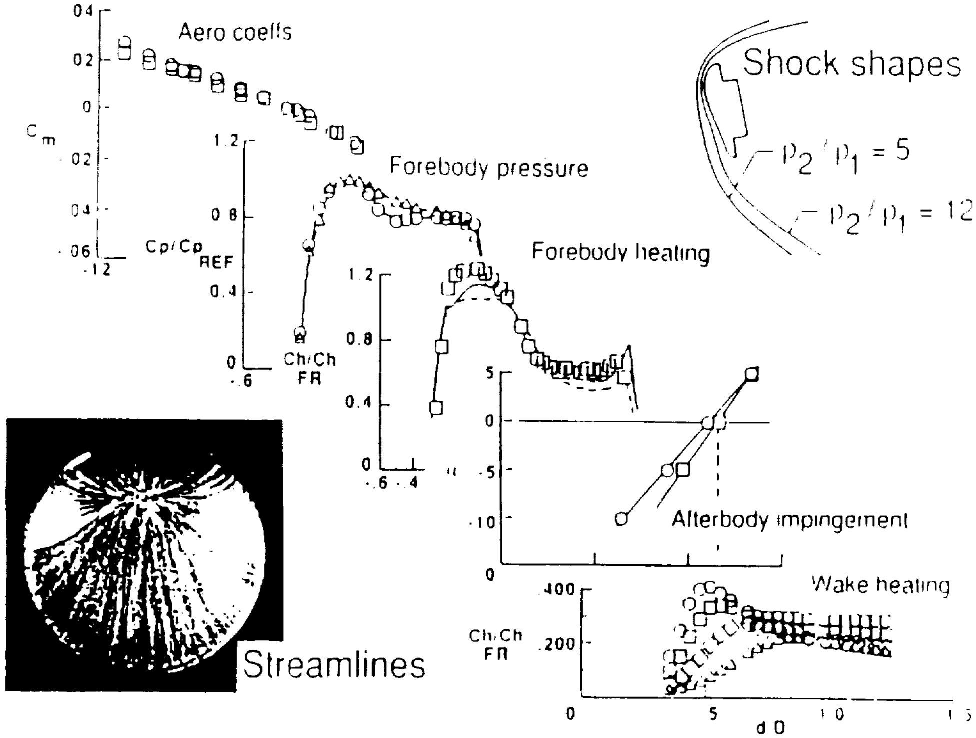
High L / D
Ablative Heatshield
Internal Payload

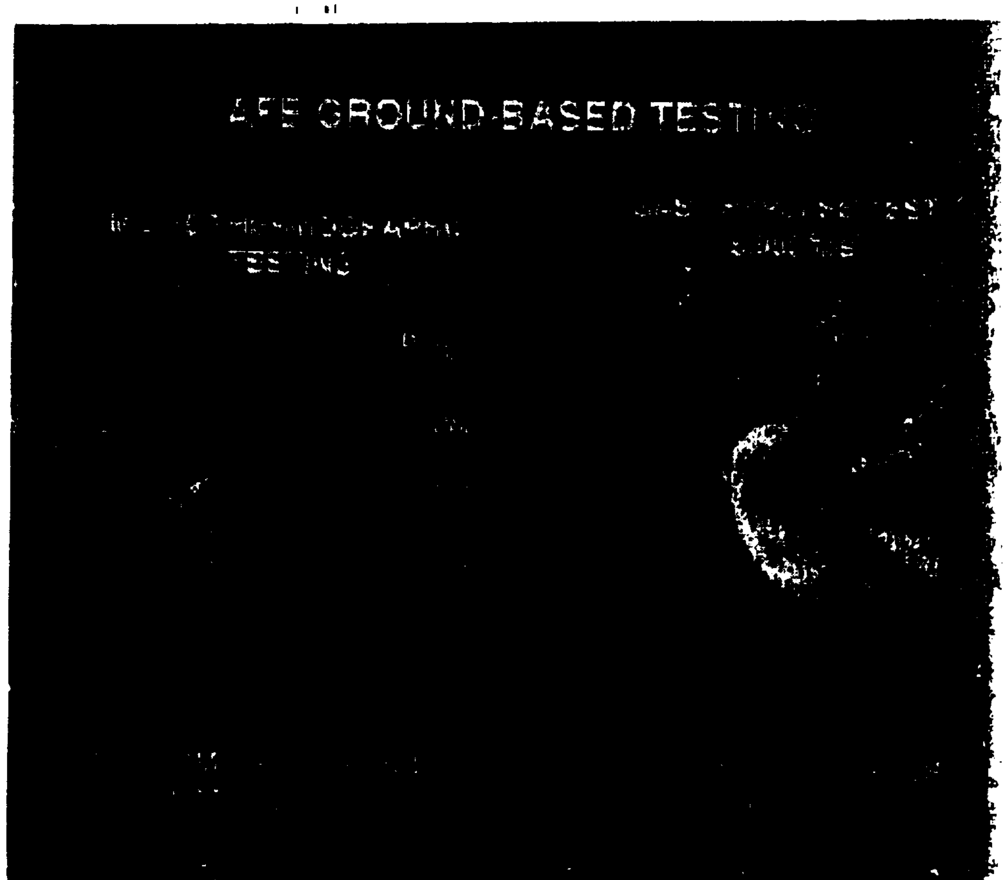
AFE THIN-FILM HEAT TRANSFER MODEL IN 31-INCH M=10 TUNNEL



AFE EXPERIMENTAL DATA BASE

EAB/SSD/LaRC





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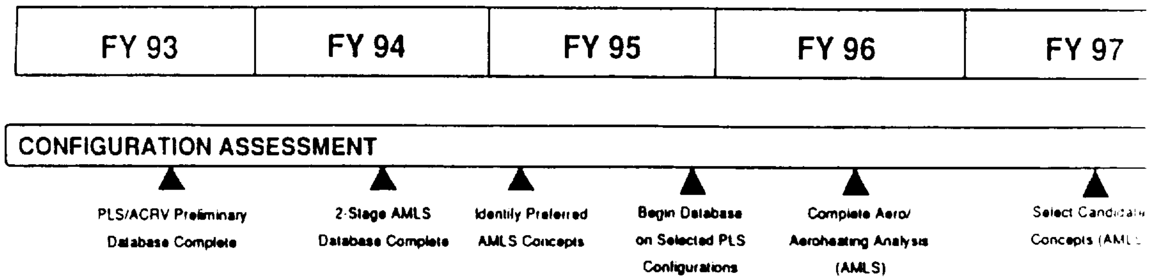
CONFIGURATION ASSESSMENT



AEROTHERMODYNAMICS BASE R&T PROGRAM

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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

- UNIQUE CAPABILITY NOT DUPLICATED IN FREE WORLD
- SUPPORTS/ENABLES ALL AGENCY MISSIONS
- RECOGNIZED OUTSIDE OAET AS ABSOLUTELY REQUIRED FOR GROWING NUMBER OF FUTURE VEHICLES
- PRESENT LEVEL OF EFFORT INSUFFICIENT
  - PACE OF THE DEVELOPMENT OF COMPUTATIONAL DESIGN AND ANALYSIS TOOLS
  - ADEQUACY OF EXPERIMENTAL CAPABILITY TO VALIDATE SUCH TOOLS AND PROVE DESIGN CONCEPTS
  - APPLICATION OF VALIDATED TOOLS AND FACILITIES FOR CONFIGURATION DESIGN AND ASSESSMENT

AEROTHERMODYNAMIC TECHNOLOGY WILL GREATLY INFLUENCE THE VIABILITY AND AFFORDABILITY OF ALL FUTURE SPACE TRANSPORTATION SYSTEMS.

NASA

AEROBRAKING (Aeroassist) for Transportation Thrust

External Review of Integrated Technology Plan for the Civil Space Program

June 27,1991

SEI

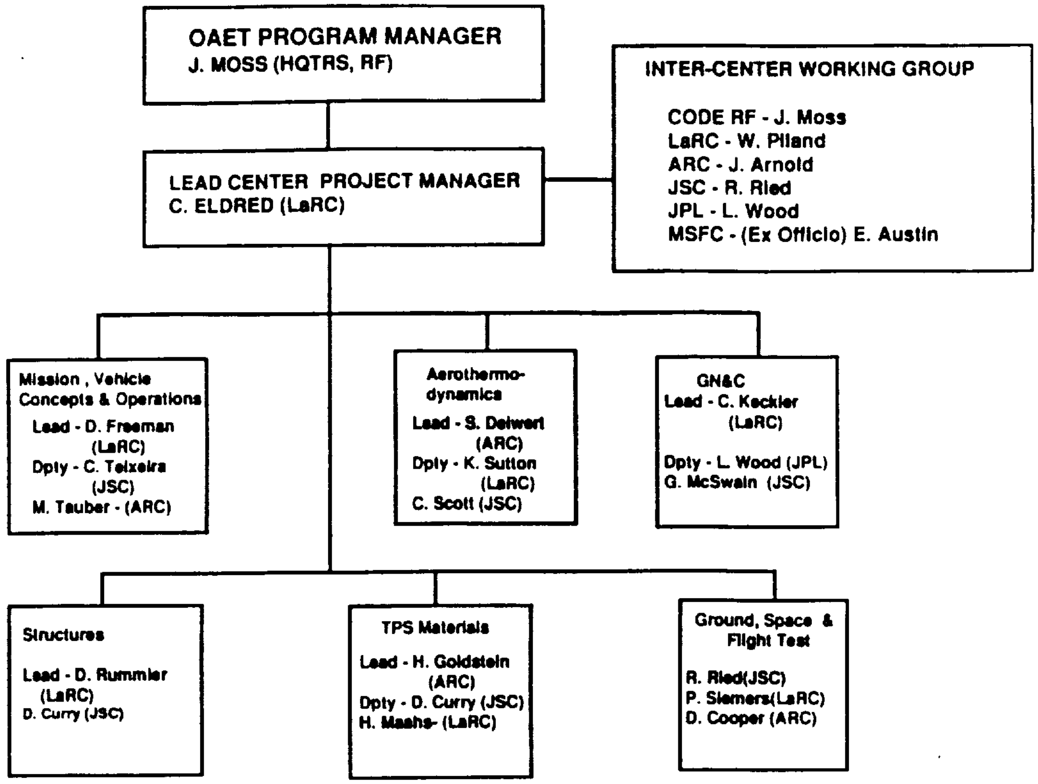
NASA

Aerobraking

- Definitions
- Applications/Benefits
- Environments
- Issues
- Performance Objectives
- Technology Program
- Synthesis Report

SEI

AEROBRAKE TECHNOLOGY ORGANIZATION



4/19/91

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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

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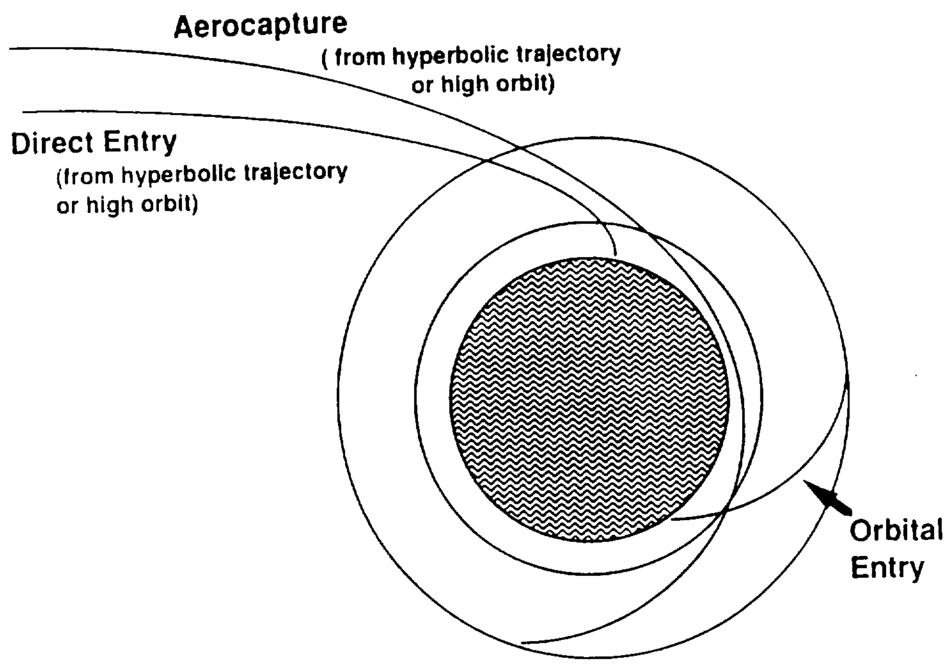
AEROBRAKING MODES



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AEROBRAKING APPLICATIONS

	All Chemical	Chemical/ Aerobrake	Nuclear Thermal
Lunar Return			
Aerocapture	N/A	Baseline	N/A
Direct Entry	Baseline	--	
At Mars			
Aerocapture	--	Baseline	Option
Direct Entry	--	Option	Option
Entry from orbit	Baseline	Baseline	Baseline
Mars Return			
Aerocapture	--	Option	Option
Direct Entry	Baseline	Baseline	Baseline

Aerobraking provides many viable mission options.

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Aerobraking Applications to Mars Precursor and Robotic Missions

Mars Sample Return (2005 Time Frame)

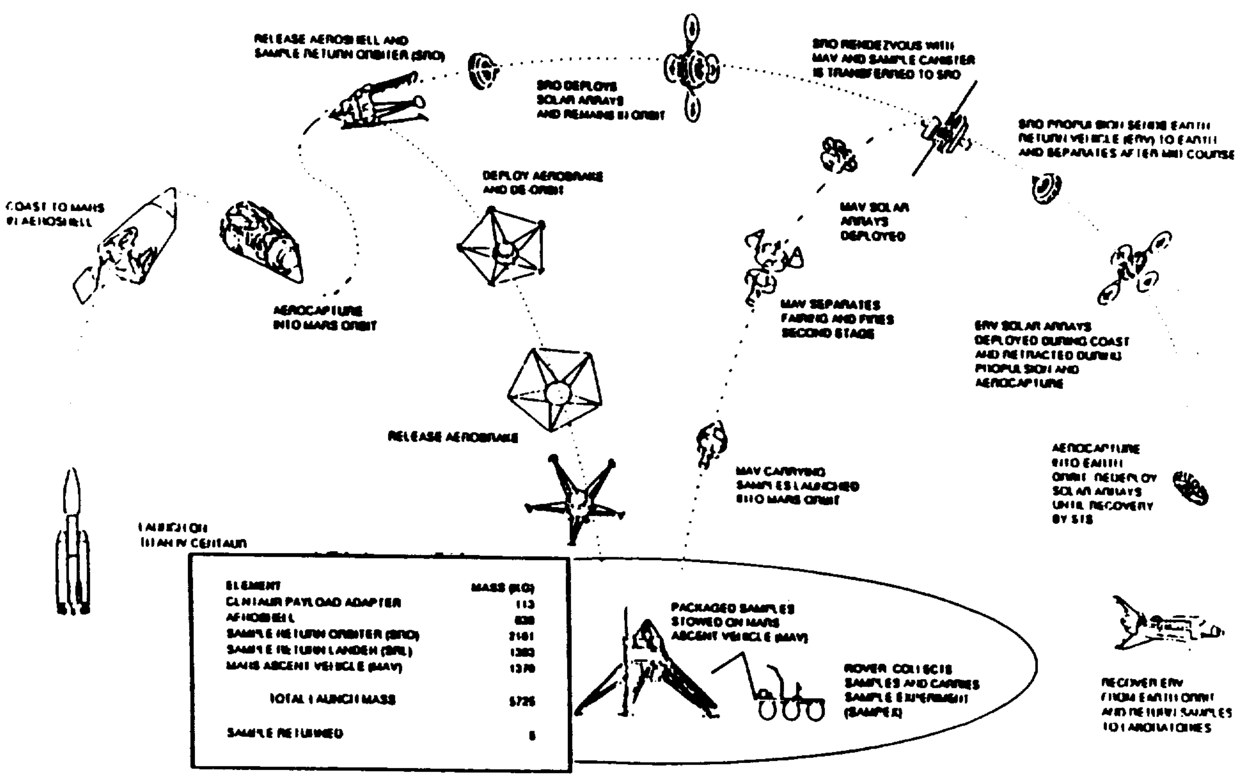
- Chemical propulsive departure for Mars
- Aerobrake to Mars Orbit
- Separate from Earth Return Vehicle
- Aeroentry and land
- Deploy Rover and collect sample
- Ascend to orbit and rendezvous with Earth return stage
- Transfer sample
- Chemical propulsive departure for Earth
- Aerobrake to orbit or aeroentry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

Mars Site Characterization Landers (2010 Time Frame)

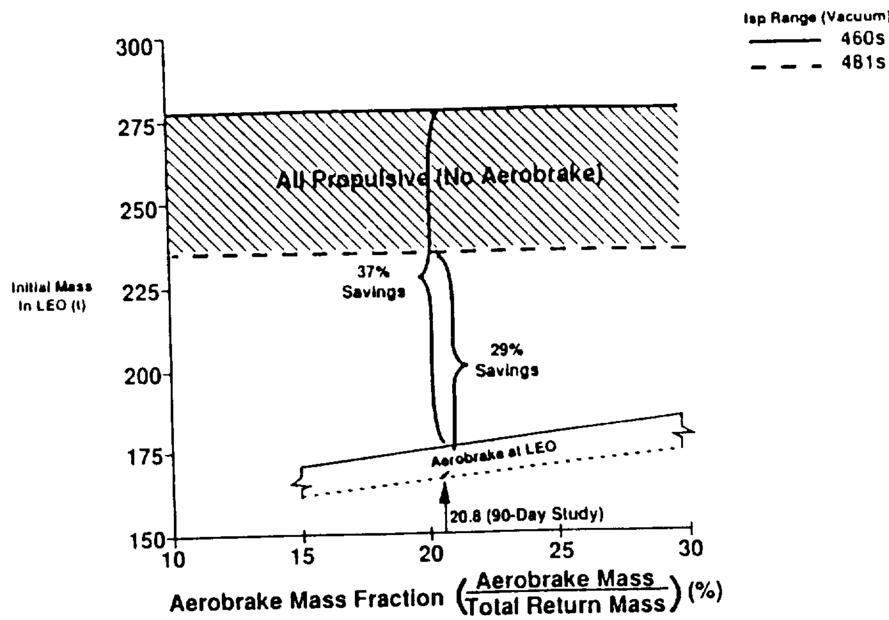
- Chemical propulsive departure for Mars
- Aerobrake or chemical brake to Mars orbit
- Aeroentry and precision landing

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



Benefits of Lunar Aerobraking



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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.

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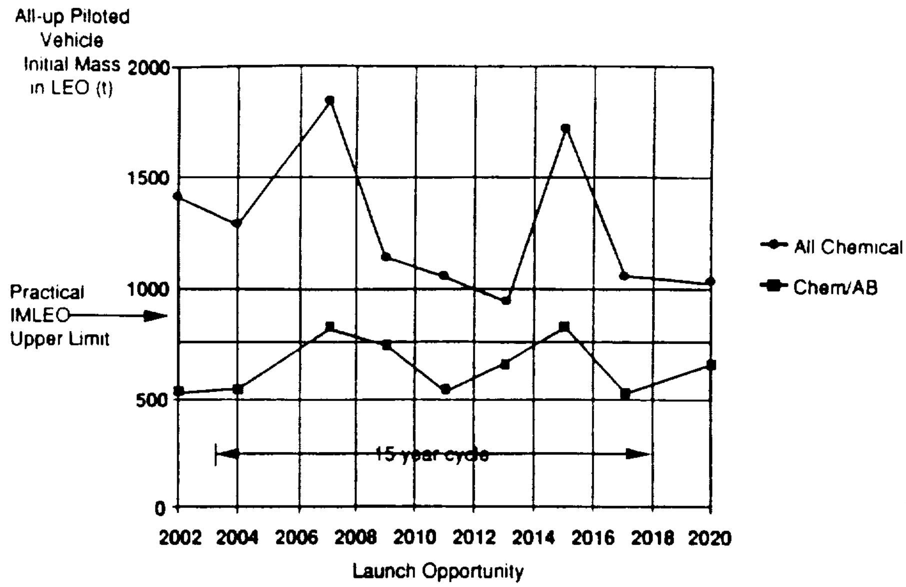
Mars Short Duration Stay Venus Swing-By Missions



Short duration stay Mars missions are not practical for Chemical systems without Aerobrake

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

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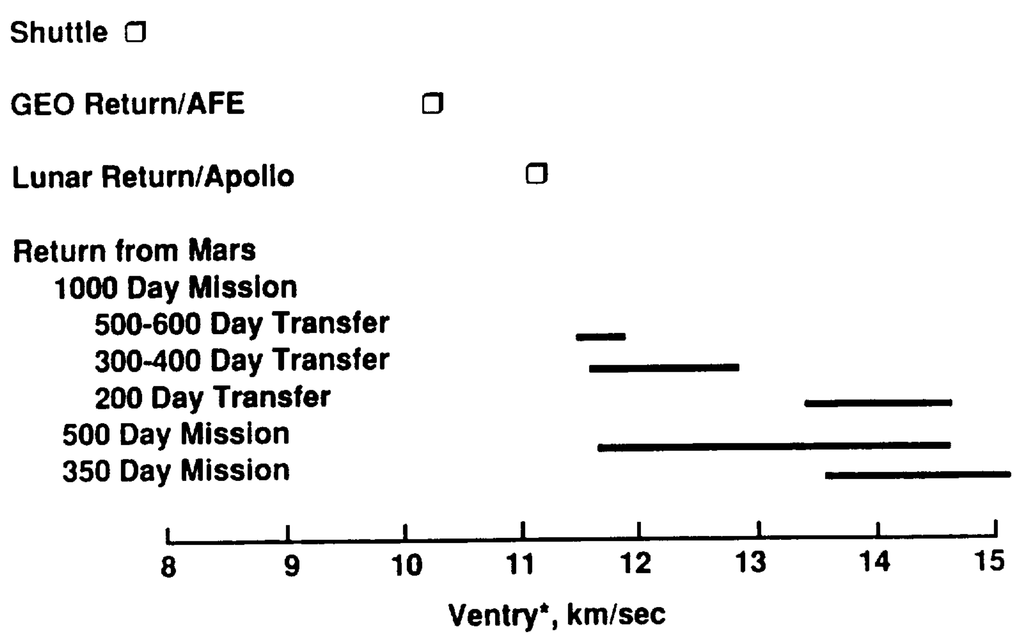
EARTH ENTRY VELOCITY ENVELOPES



* Inertial

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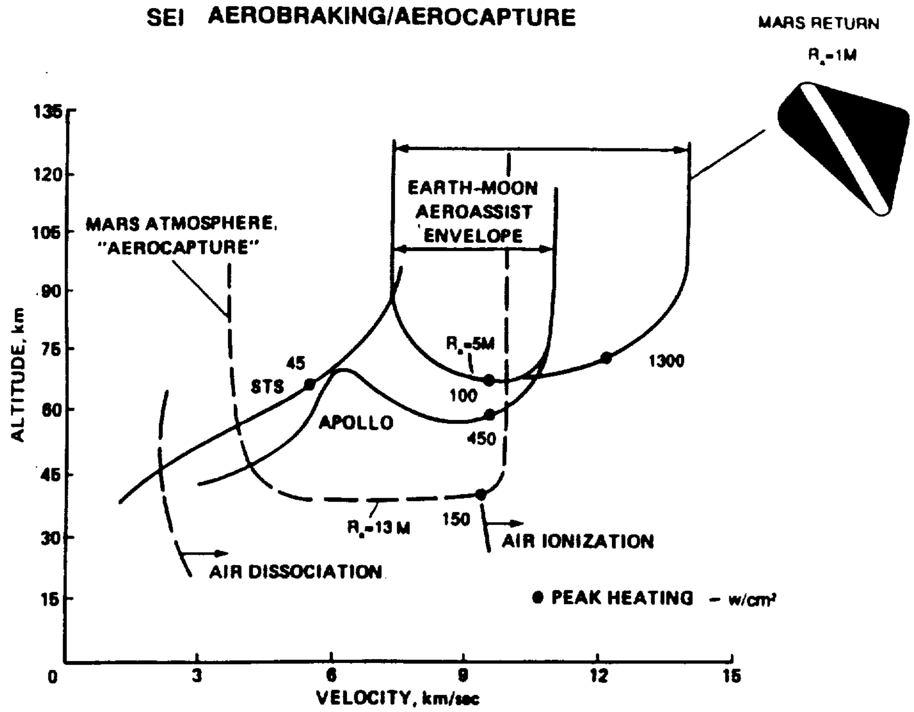
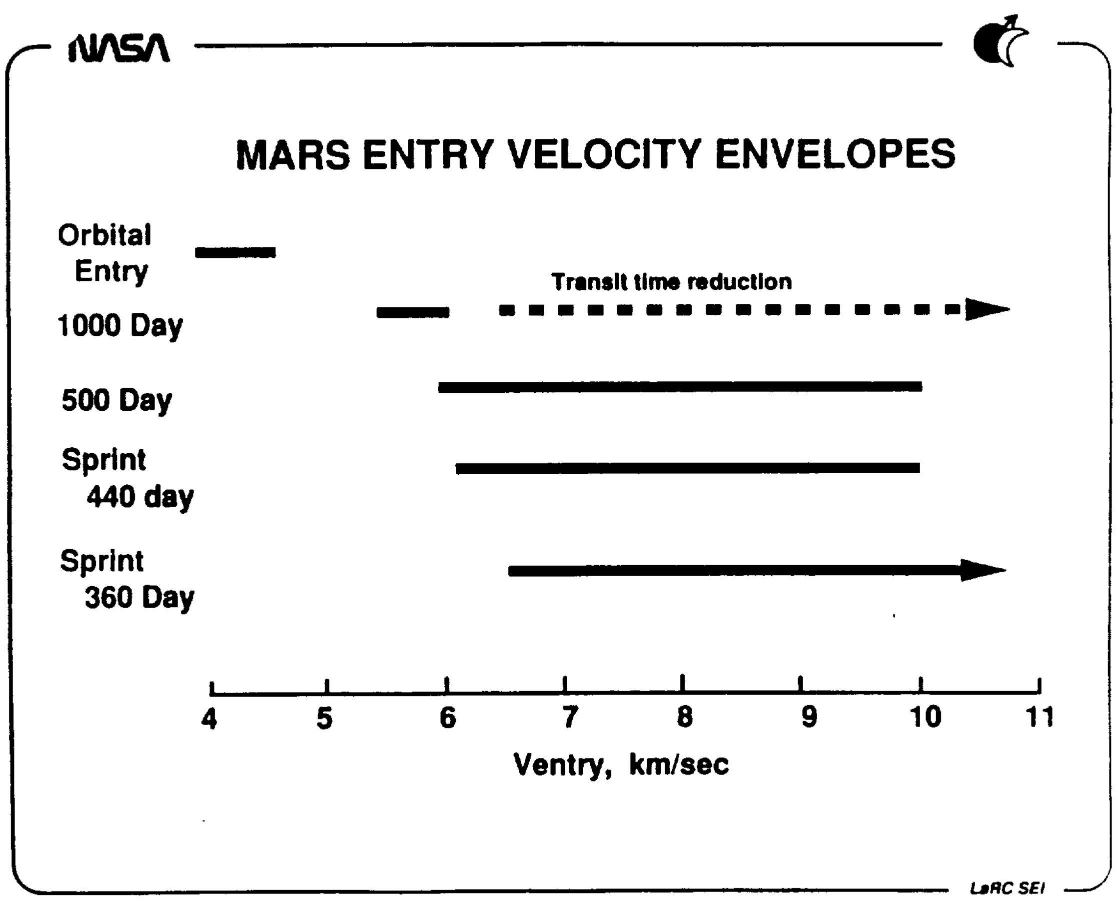

SEI AEROBRAKING/AEROCAPTURE
MARS RETURN
R_n=1M
EARTH-MOON AEROASSIST ENVELOPE
MARS ATMOSPHERE, "AEROCAPTURE"
ALTITUDE, km
135
120
105
90
75
60
45
30
15
0
3
6
9
12
15
VELOCITY, km/sec
45
STS
APOLLO
R_n=5M
100
1300
450
R_n=13M
150
AIR IONIZATION
AIR DISSOCIATION
● PEAK HEATING - w/cm²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MARS ENTRY VELOCITY ENVELOPES
Orbital Entry
1000 Day
Transit time reduction
500 Day
Sprint 440 day
Sprint 360 Day
4
5
6
7
8
9
10
11
Ventry, km/sec
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Aerobraking Challenges and Issues

There are no showstoppers

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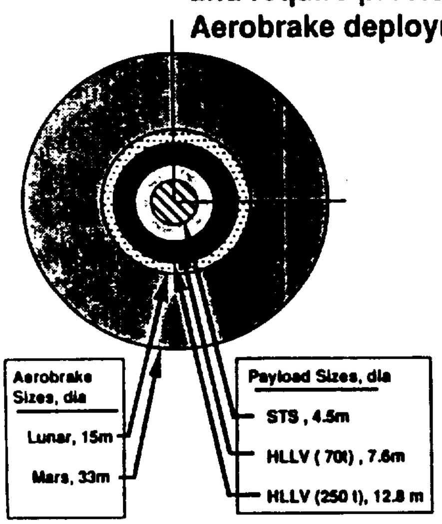
Aerobrake Deployment/Assembly

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.

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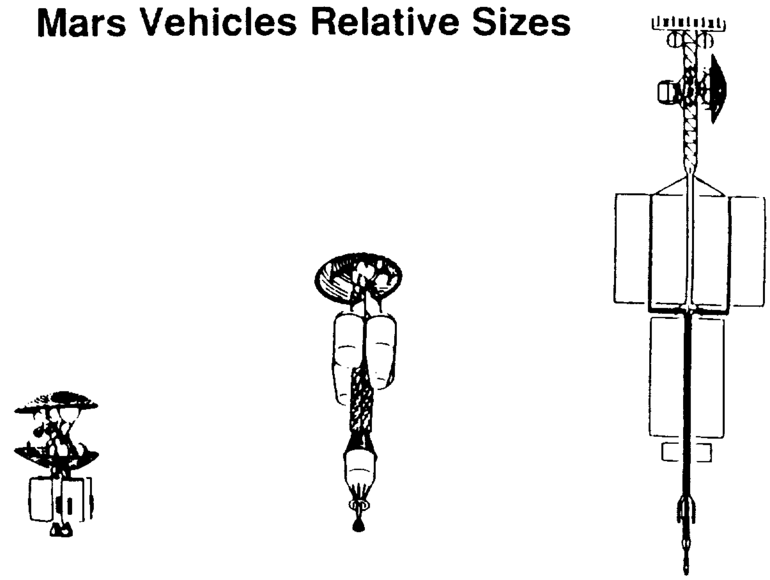
Mars Vehicles Relative Sizes



Option	Chem/Aerobrake	Nuclear Thermal	Nuclear Electric
Length	50m	110 m	230m

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

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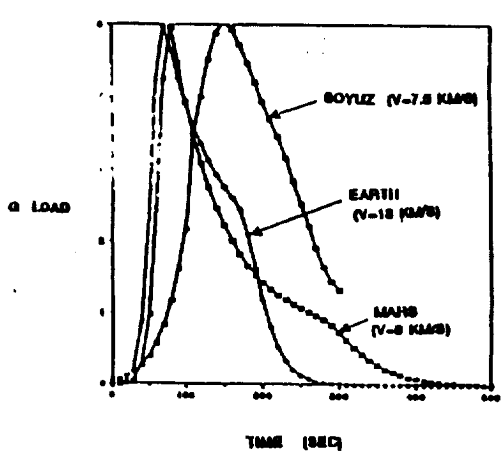
CREW G-LOADS DURING AEROBRAKING

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

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READAPTATION TO 1 G FOLLOWING PROLONGED SPACEFLIGHT

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

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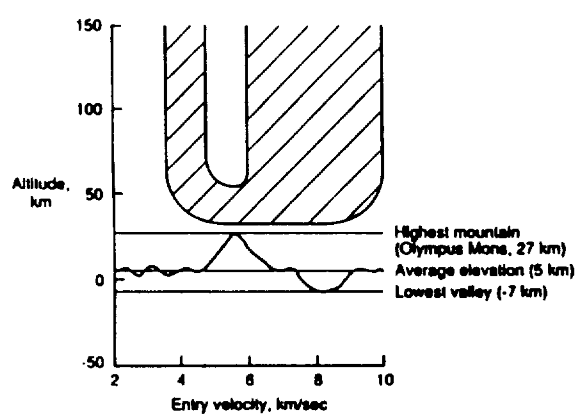
Mars Aerocapture Altitude Boundaries

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.

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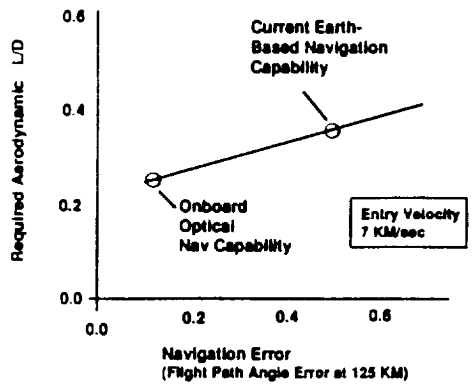
NAVIGATION ACCURACY FOR MARS AEROCAPTURE

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

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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.

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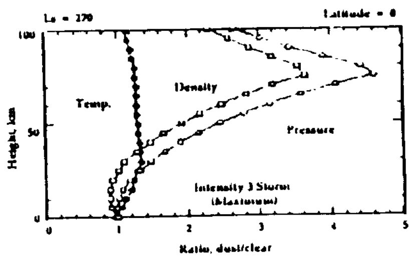
ATMOSPHERIC VARIATIONS & UNCERTAINTIES

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



Atmosphere:

- 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.

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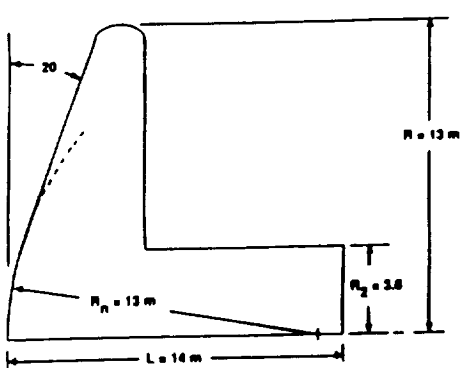
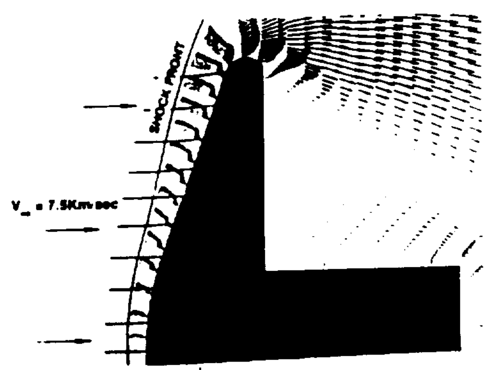
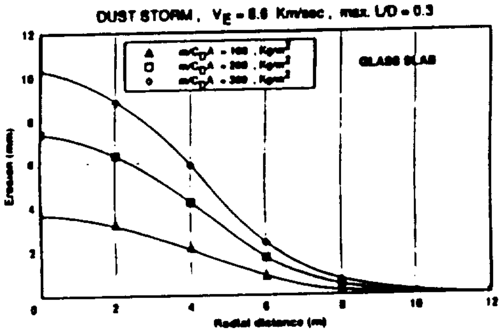
AEROBRAKING IN A DUSTY MARTI/ .TMOSPHERE



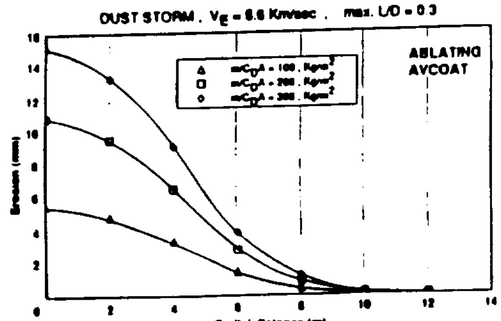
Vehicle configuration.



Dust particle trajectories in the shock layer.



EROSION OF GLASS SLAB



EROSION OF ABLATING AVCOAT

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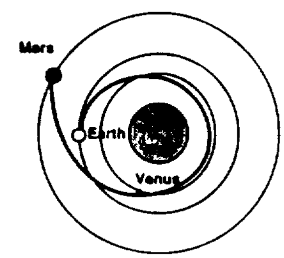
RADIATION ENVIRONMENT

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.



Inbound

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KEY ELEMENTS OF AEROBRAKING TECHNOLOGY

An Integrated Program

- Integration of mission, design and technology issues
- Multidisciplinary technologies
  - Aerothermodynamics
  - GN&C
  - Thermal Protection
  - Structures
- Validation
  - Ground test
  - Flight test

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AEROBRAKING PERFORMANCE OBJECTIVES

TECHNOLOGY GOAL/ PARAMETER	CURRENT SOA	OBJECTIVE/REQUIREMENT
VEHICLE CONFIGURATION	L/D = .25-.3, ground based	L/D 0.5 with mission margin and flexibility
AEROTHERMODYNAMICS	3-D models for non-equilibrium conditions, with very limited validation database	Validated 3-D gas codes, chemical and thermal rarefied flows, Mars gases, coupled radiative heating/massive ablation limited, validation database
GUIDANCE, NAVIGATION & CONTROL	Entry to precise Earth surface	Aerobraking to precise planetary orbit; precision landing to Mars surface; autonomo navigation; adaptive, fault tolerant systems
THERMAL PROTECTION SYSTEM	Reusable < 2800 - 3000°F; Ablative: moderate-energy (Apollo)	Light-weight reusable materials (lunar), increased reuse temp to ~ 4000°F Low weight ablative materials for high energy missions at Mars and Earth return
STRUCTURES	Structures and TPS are ground based	Aerobrake mass fraction < 15%, on-orbit assembly and certification
SYSTEM LEVEL PARAMETERS		
ENTRY VELOCITY @ PLANET	4.5 km/sec	8.5-10 km/sec
ENTRY VELOCITY @ EARTH	11 km/sec	12 - 15 km/sec
MANRATING	Manned Entry, Unmanned Aerobrake	Manned Aerobrake

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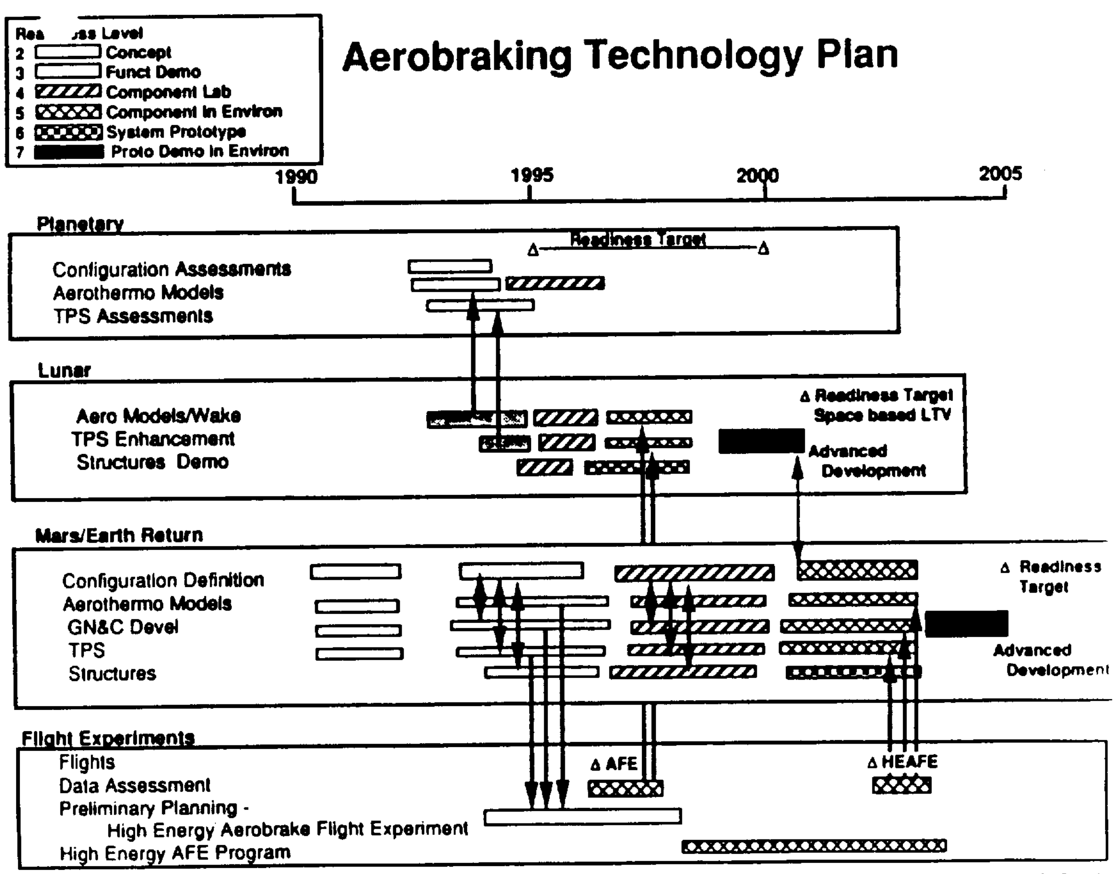

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Space Transportation Systems

Aerobraking

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

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

6/10/91 CHF

Aerobraking Suo-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 rqmnts
- 1993 Define planetary technology rqmnts
- 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

6/6/91 CHE

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

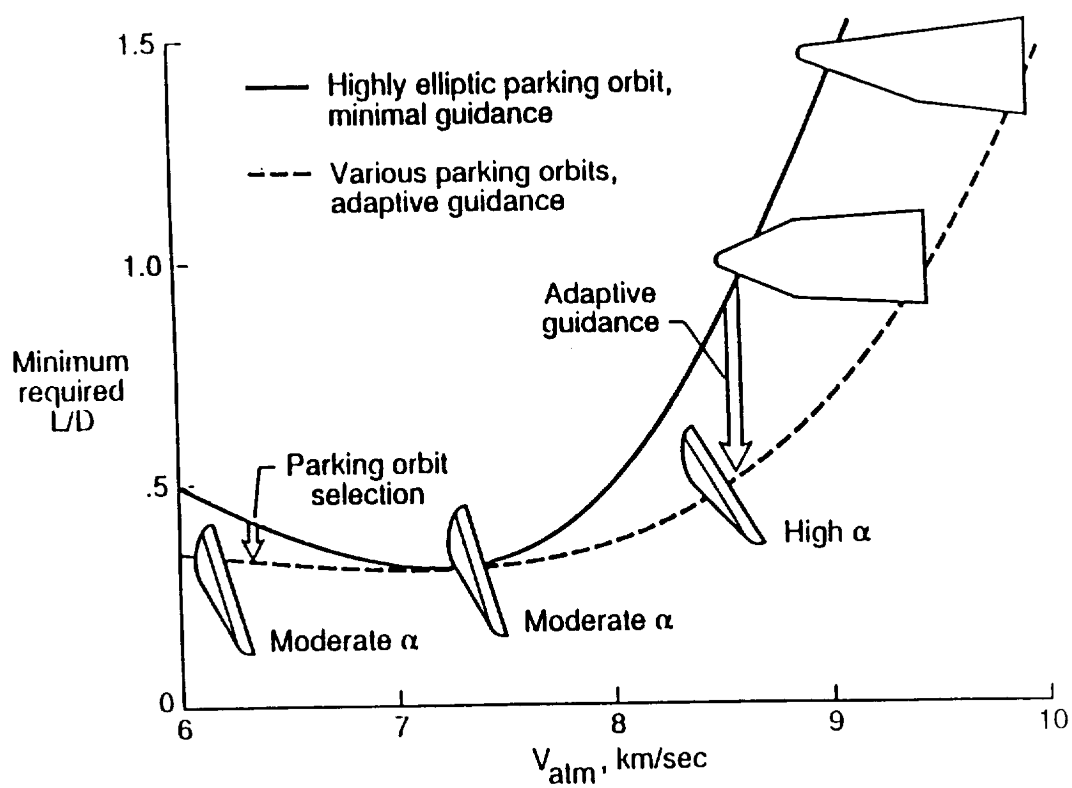
Drawbacks to high L/D aerobrake configurations

- 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

:NIMUM AEROBRAKE L/D . OR MARS AEROCAPTURE
1° CORRIDOR WIDTH REQUIREMENT, 5-G DECELERATION LIMIT



Aerobraking Sub-element

Aerothermodynamics

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

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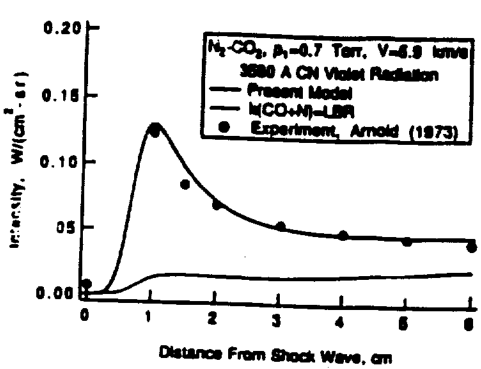
VALIDATION OF SEI AEROTHERMODYNAMICS CODES
TWO-TEMPERATURE MODEL VS EXPERIMENTS

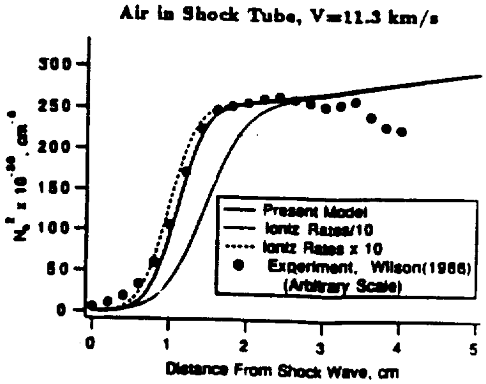
MARS ENTRY

N_2-CO_2 Mixture in Shock Tube, V=6.9 km/s

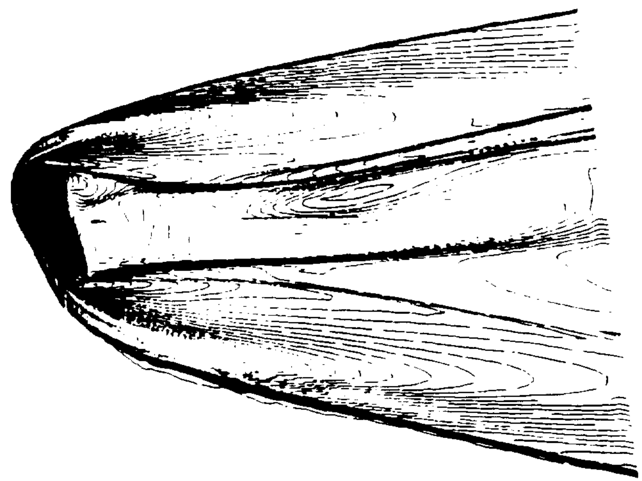


LUNAR RETURN

Air in Shock Tube, V=11.3 km/s



STATE-OF-THE ART CFD FOR REAL GAS FLOWS



Temperature Contours

Aerobraking Sub-element

Guidance, Navigation and Control

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
- Validatible adaptive guidance algorithms
- Atmospheric density sensors
- Test bed/flight demonstration

SCHEDULE

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

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

PARTICIPANTS

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

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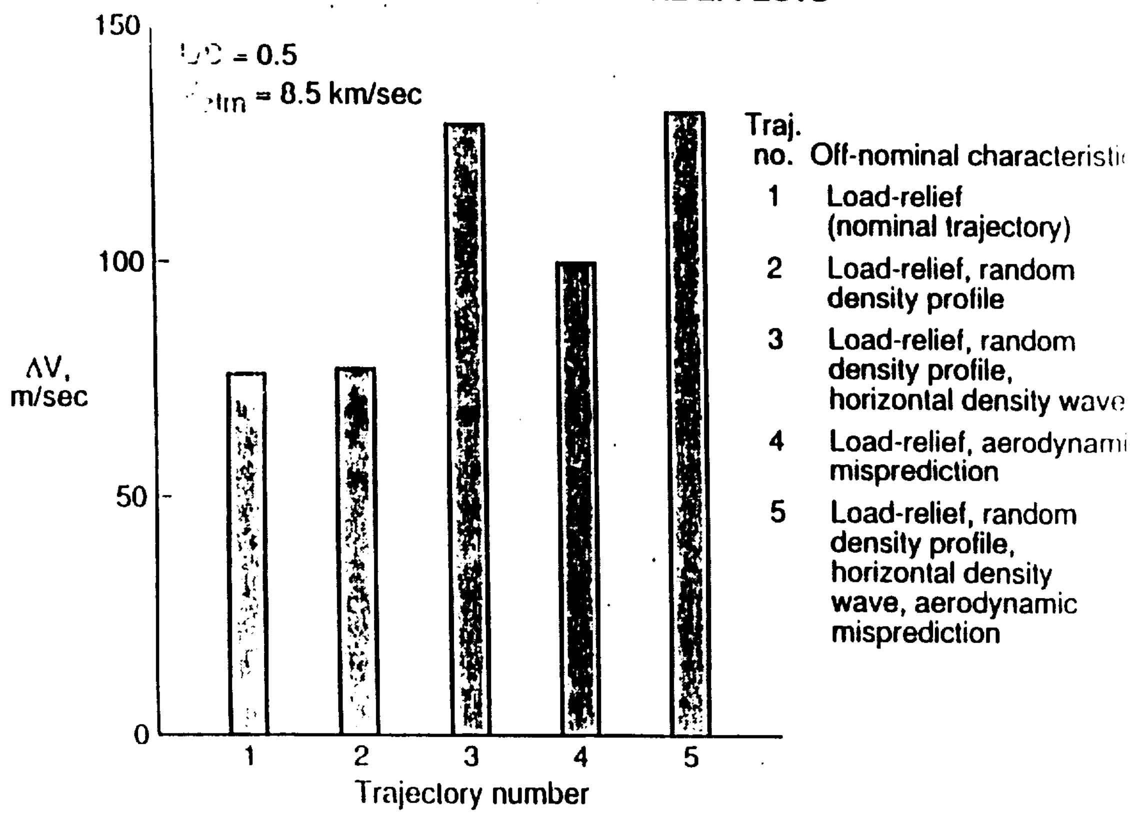
ADAPTIVE GUIDANCE METHODS

- 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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Thermal Protection Materials

OBJECTIVES

- 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 rqmnts for manned & robotic missions
- 1994 Evaluate materials for MRSR mission
  Define rqmnts for manned Mars missions
- 1995 Define TPS experiments 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/structures
- JSC
  Carbon-carbon materials
  Material validation

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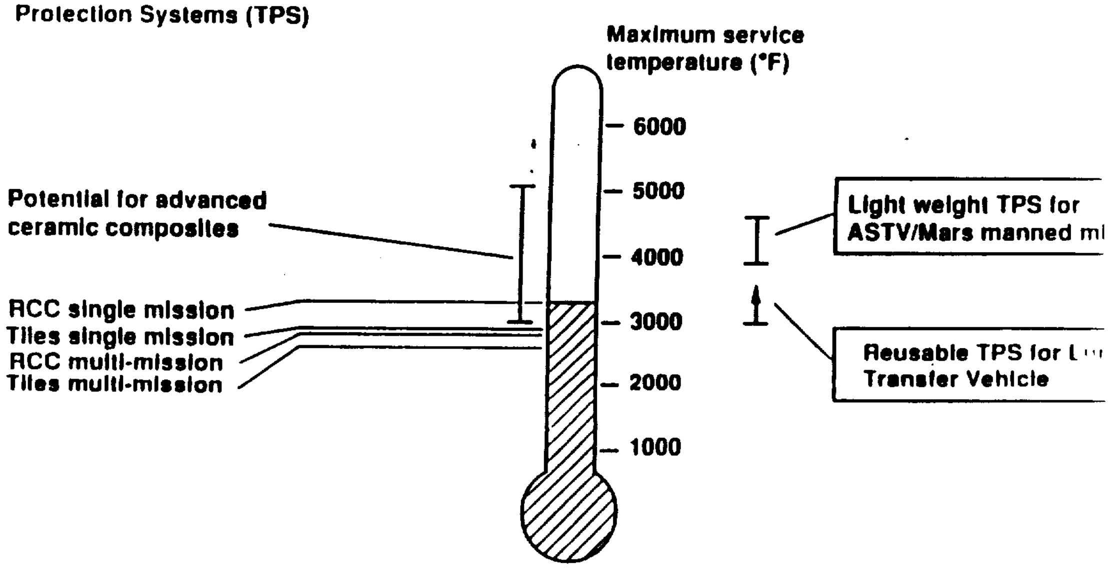
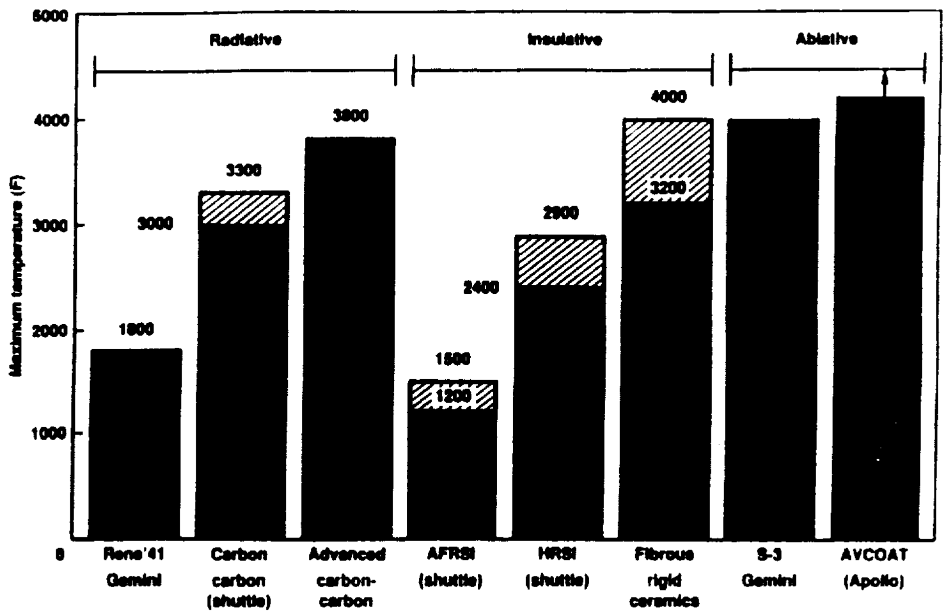
Reusable Thermal Protection Systems (TPS)



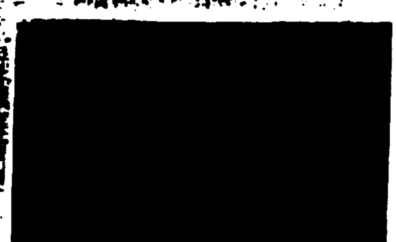
- **Development of higher temperature TPS materials is a NASA critical techn**

THERMAL PROTECTION SYSTEMS TEMPERATURE CAPABILITY



POST-TEST PHO GRAPHS OF RCC AND ZrB_2 + 20 v/o SiC SAMPLES

conditions: Test time = 3 min, Cold wall heat flux = 240 BTU/ft²-sec
Stag. pressure = 0.046 atm, Stag. enth. = 10,800 BTU/lbm



LTV -t1n2a
RCC

Recession: 78 mils
Weight change: 1.31 gm
Peak temp.: 3700°F

SiC coating lost after approximately 100 sec

Cerac - t2n4a
ZrB_2 + 20 v/o SiC

Recession: -1 mils
Weight change: 0.01 gm
Peak temp.: 3300°F

Adherent, thin, glassy coating formed on sample

NASA Ames Research Center Thermal Protection Materials Branch

Structures

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

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

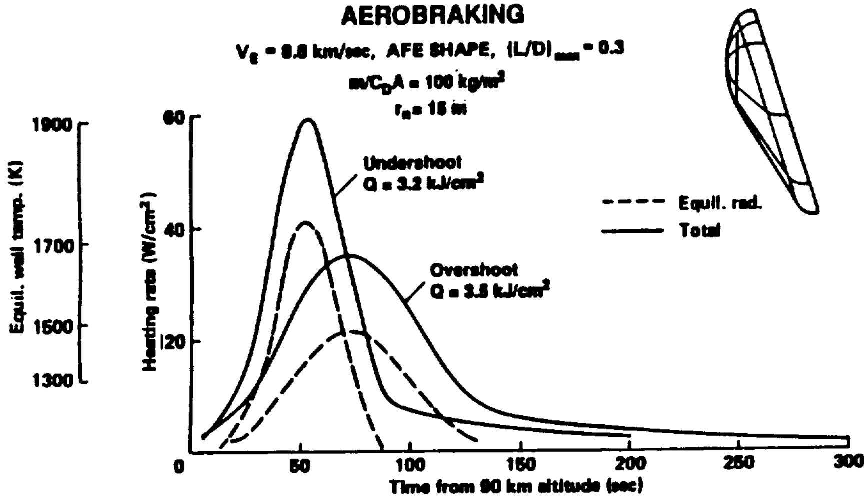
PARTICIPANTS

- 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.

6/14/91

STAGNATION POINT HEATING PULSES DURING MARS AEROBRAKING



MASS FRACTION = 13 %

Including Fundamental Integration Concerns

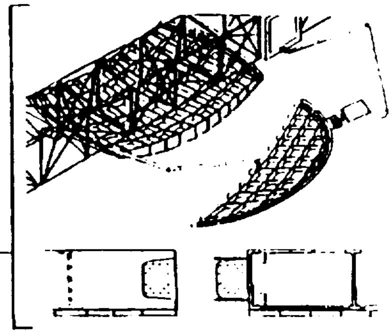
Fully configured aerobrakes are too large to launch inside a rocket payload shroud

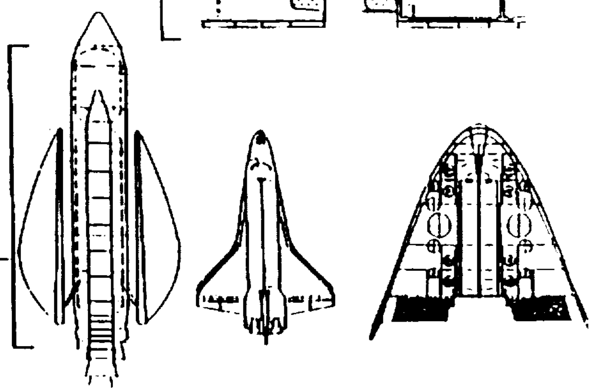
Flexible structure solutions

- **Foldable**
  - **Martin Marietta**

Rigid structure solutions

- **Assembled in space**
  - **Boeing Huntsville**
  - **McDonnell Douglas**
- **Deployable**
  - **No major effort**
- **Integral launch**
  - **Boeing Huntsville**





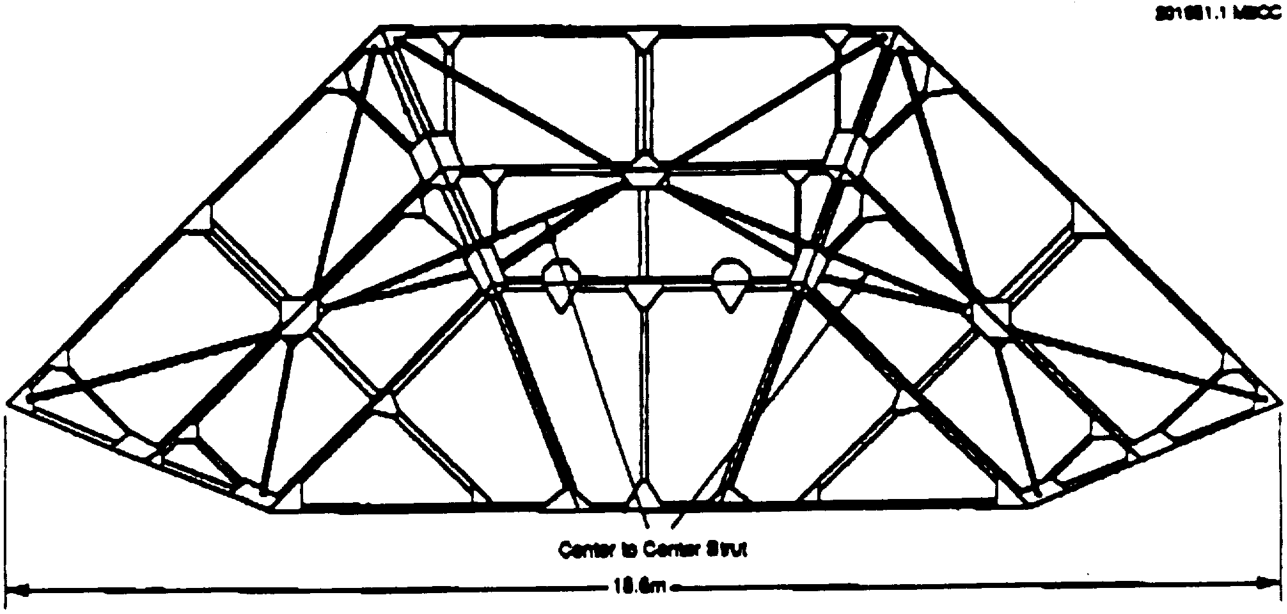


Figure 6a. Mock-Up Design

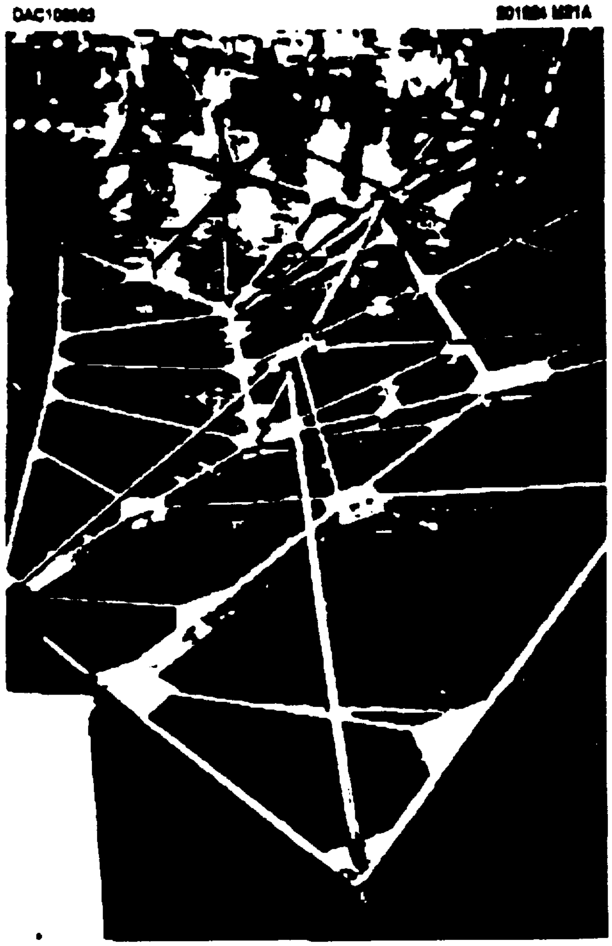


Figure 6b. Integrated Mockup

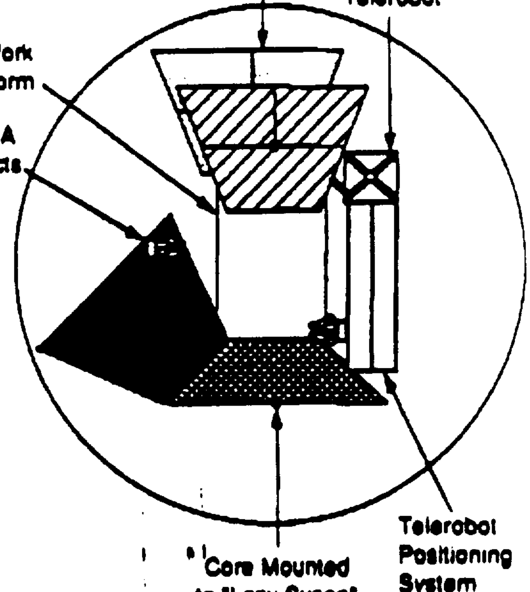


Figure 7. Mockup Layout and Proposed Assembly Operations in the UWTF

Ground and Flight Test

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

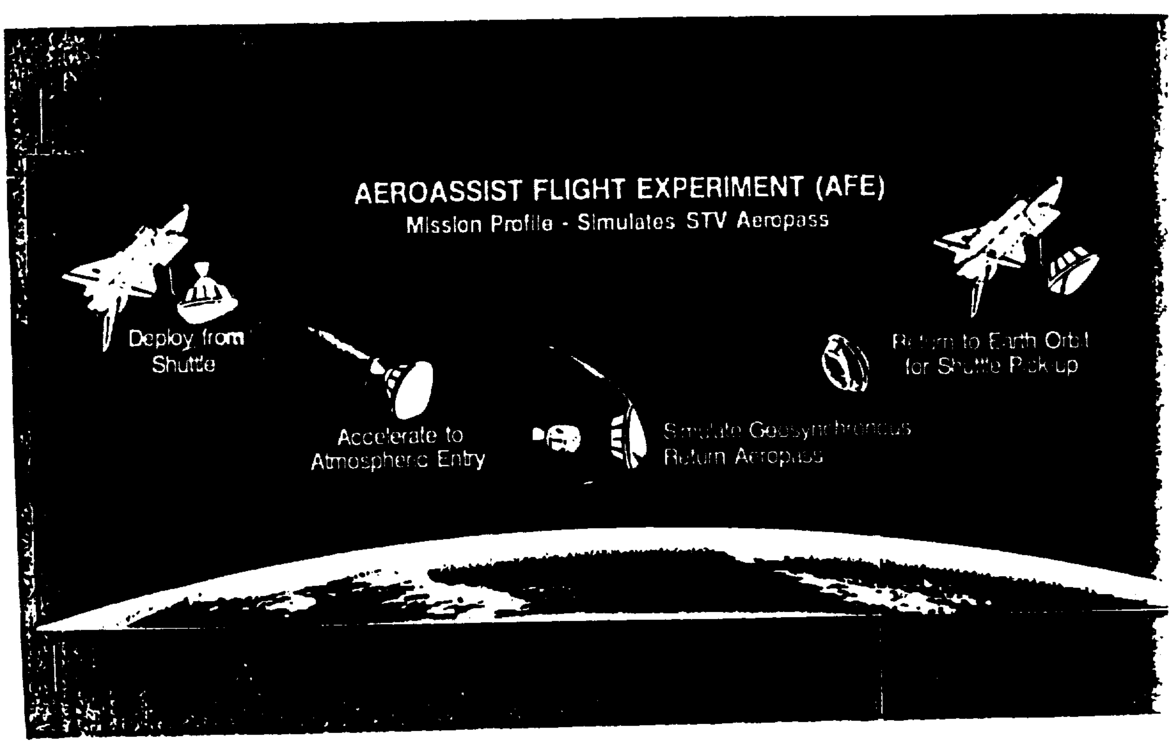
RESOURCES

- 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

6/6/91 CHF



Technology Flight Experiments

High Energy Aerobraking

OBJECTIVES

- Programmatic

  Validate and demonstrate Aerobraking technologies for manned Mars missions.

- Technical

  Validated aerothermodynamic codes
  Demonstrate high temperature TPS materials
  Adaptive guidance demonstration

SCHEDULE

- 1993 Begin concept planning
- 1997 AFE flight test
- 1997 Start experiment development
- 2002 HEAFE flight test
- 2004 Mars mission validation
  Codes, GN&C, TPS, Structures

RESOURCES

- 1997 $20M
- 1998 $60M
- 1999 $110M
- 2000 Continue

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

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

Advocacy Chris I. LaRC CHE SEI

AEROASSIST FLIGHT EXPERIMENT

OAET

PRESENTATION

TO

SPACE SYSTEMS
and
TECHNOLOGY ADVISORY COMMITTEE

JUNE 27, 1991

AFE

AEROASSIST FLIGHT EXPERIMENT

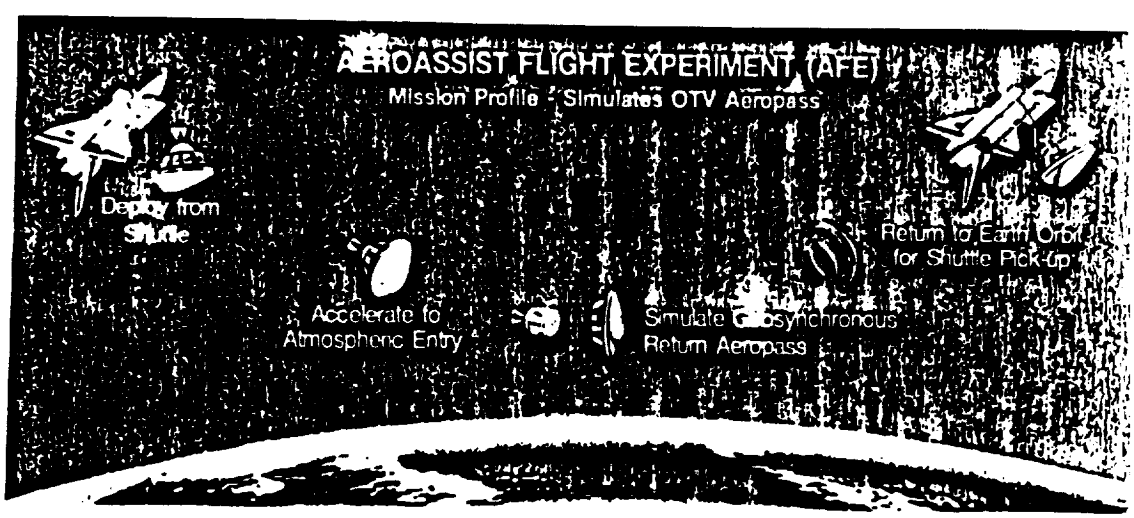
PROGRAM GOAL

- 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

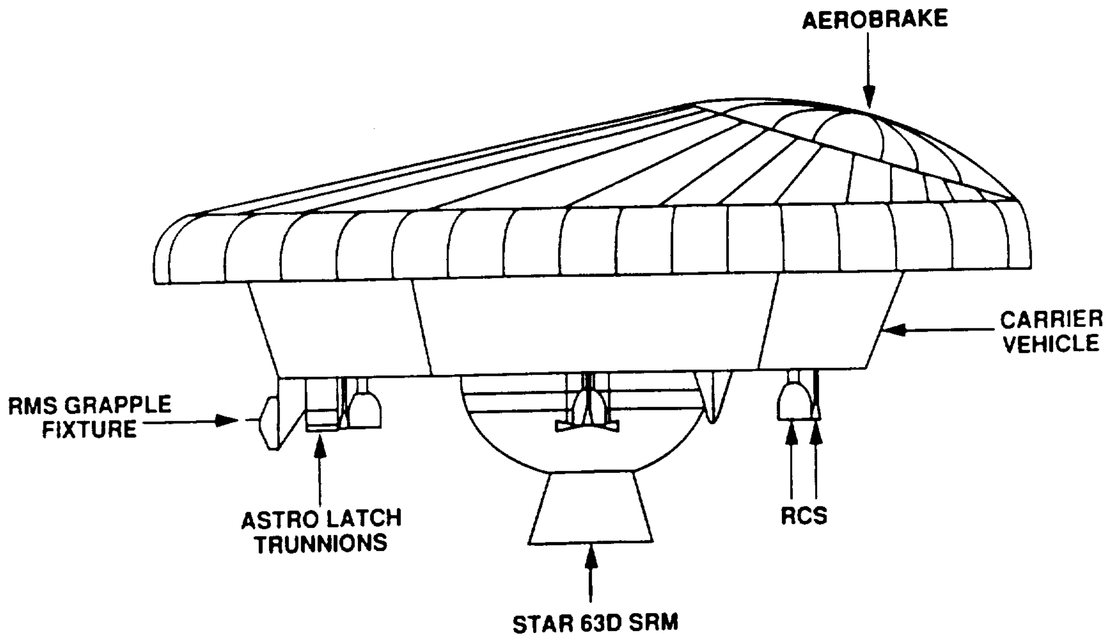
NASA



AEROASSIST FLIGHT EXPERIMENT (AFE)

OAET

DEPLOYMENT CONFIGURATION



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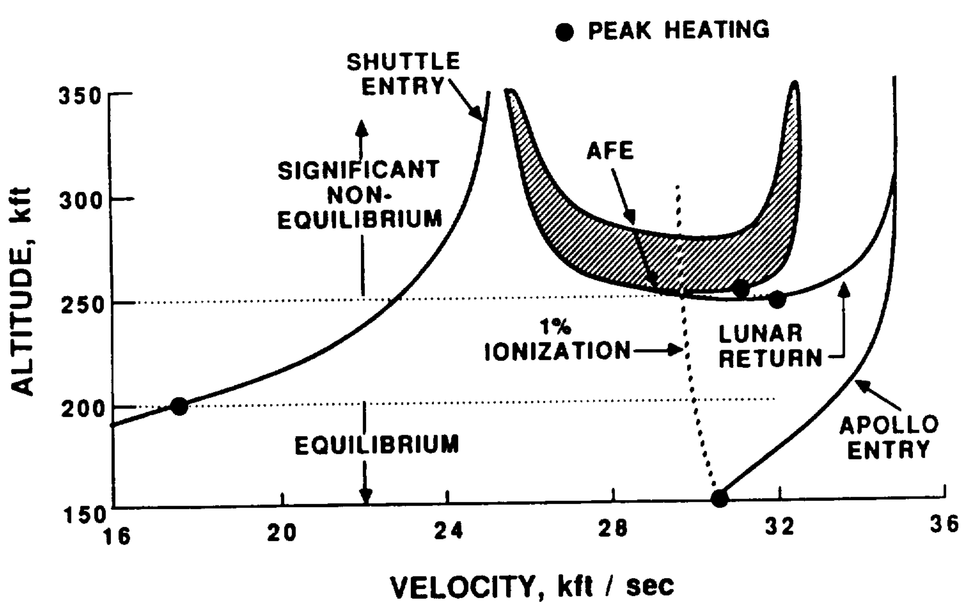
ASTV FLIGHT REGIME

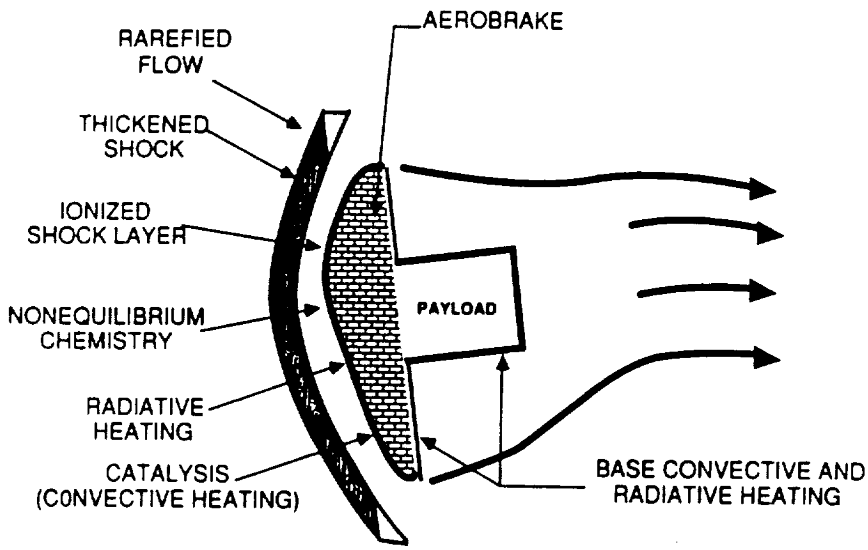
OAET



89 02..

AEROASSIST FLIGHT EXPERIMENT

ASTV FLIGHT ENVIRONMENT



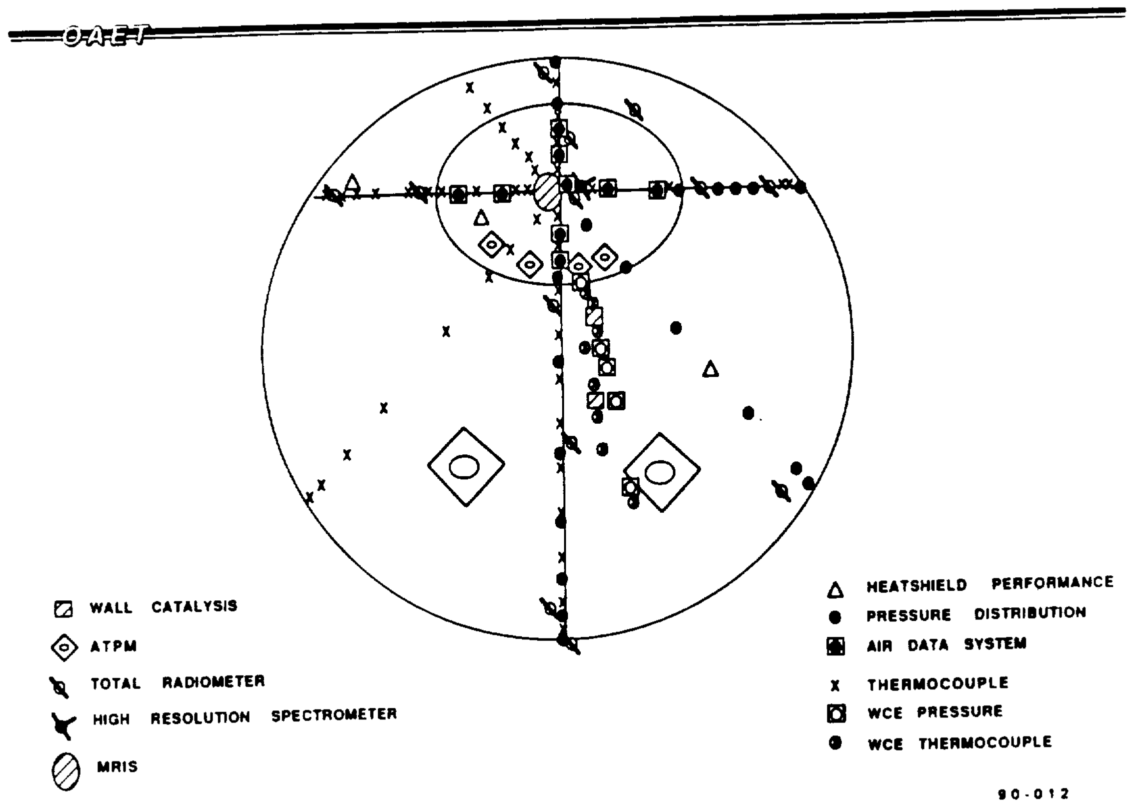
89-020A

AEROASSIST FLIGHT EXPERIMENT

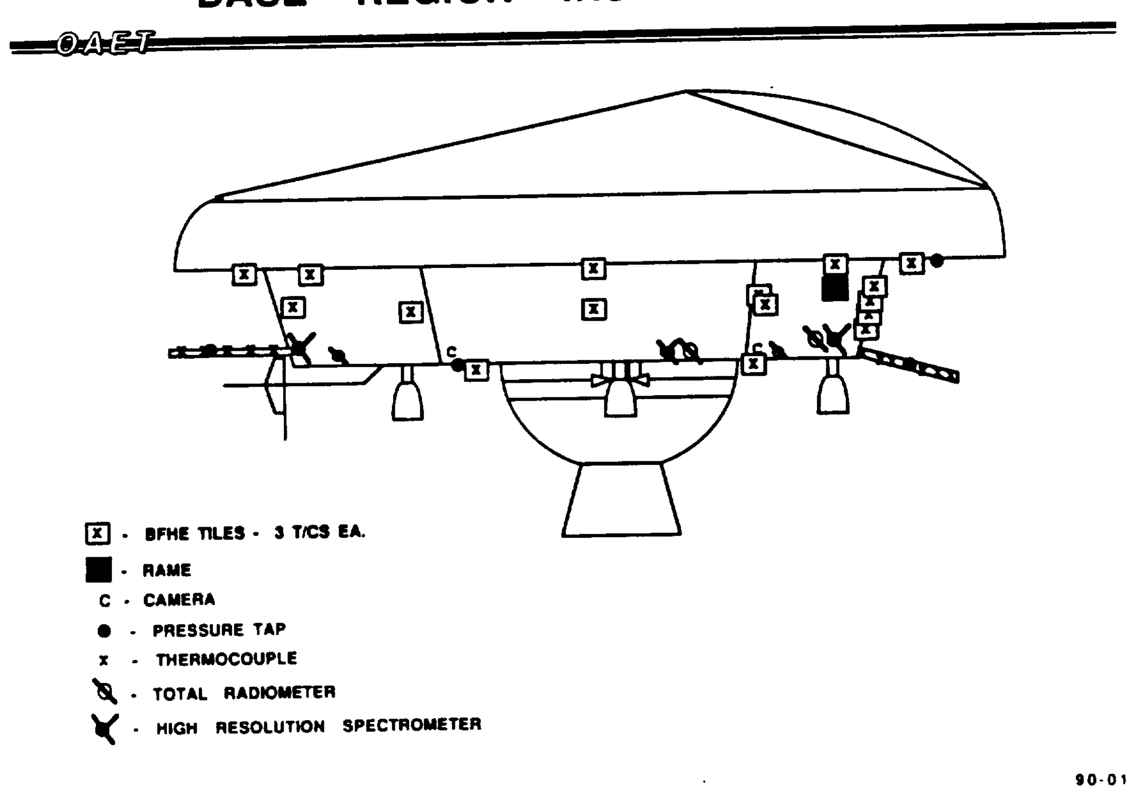
ASTV DESIGN ISSUES	AFE EXPERIMENTS
SHOCK LAYER RADIATION	o RADIATIVE HEATING EXPERIMENT (RHE) o MICROWAVE REFLECTOMETER IONIZATION SENSOR EXPERIMENT (MRIS)
SURFACE CATALYSIS	o WALL CATALYSIS EXPERIMENT (WCE)
THERMAL PROTECTION SYSTEM MATERIALS	o HEAT SHIELD PERFORMACE EXPERIMENT (HSP) o ALTERNATE THERMAL PROTECTION MATERIALS EXPERIMENT (ATPM) o FOREBODY AEROTHERMAL CHARACTERIZATION EXPERIMENT (FACE)
WAKE FLOWS/HEATING	o BASE FLOW AND HEATING EXPERIMENT (BFHE) o AFTERBODY RADIOMETRY EXPERIMENT (ARE)
AERODYNAMICS/CONTROL	o AERODYNAMIC PERFORMANCE EXPERIMENT (APEX) o RAREFIED-FLOW AERODYNAMICS MEASUREMENT EXPERIMENT (RAME) o PRESSURE DISTRIBUTION/AIR DATA SYSTEM EXPERIMENT (PD/ADS)

89-030A

AFE FOREBODY INSTRUMENTATION



BASE REGION INSTRUMENTATION

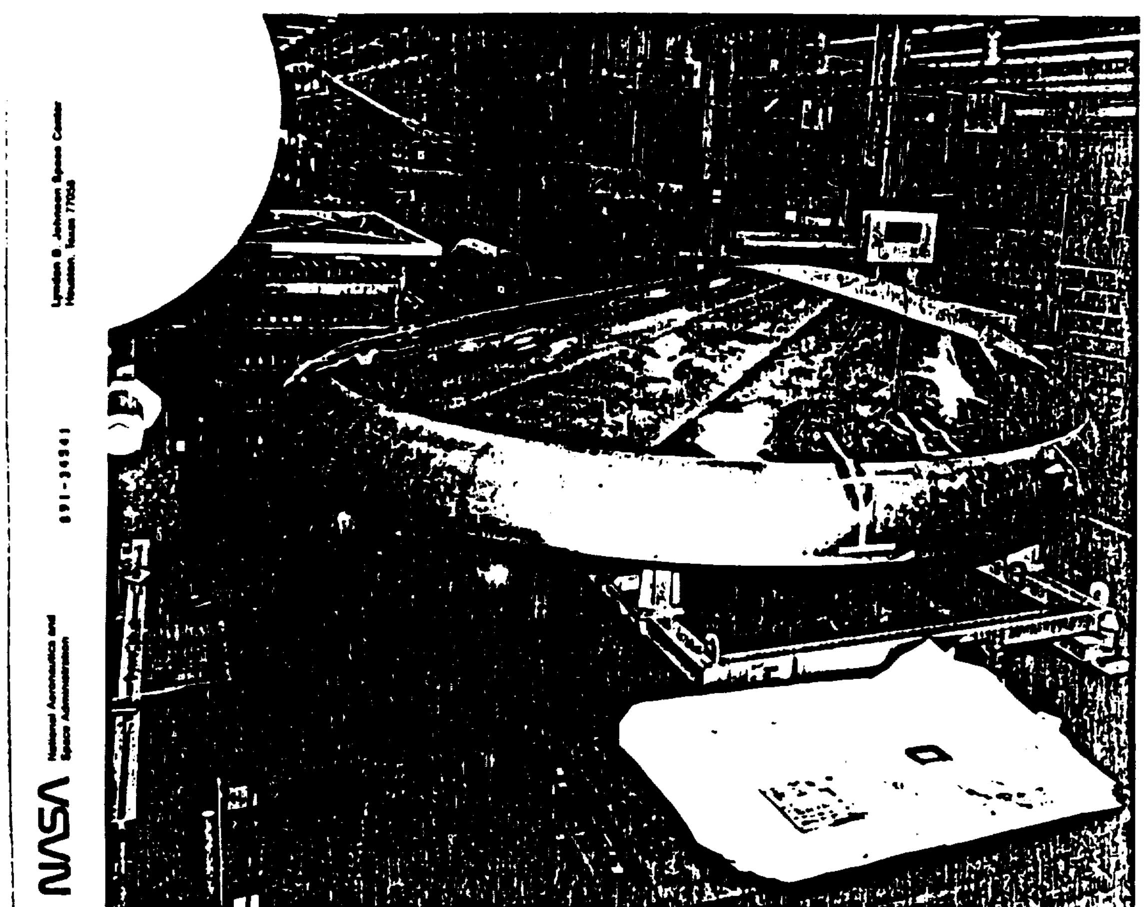


AEROASSIST FLIGHT EXPERIMENT

OAET

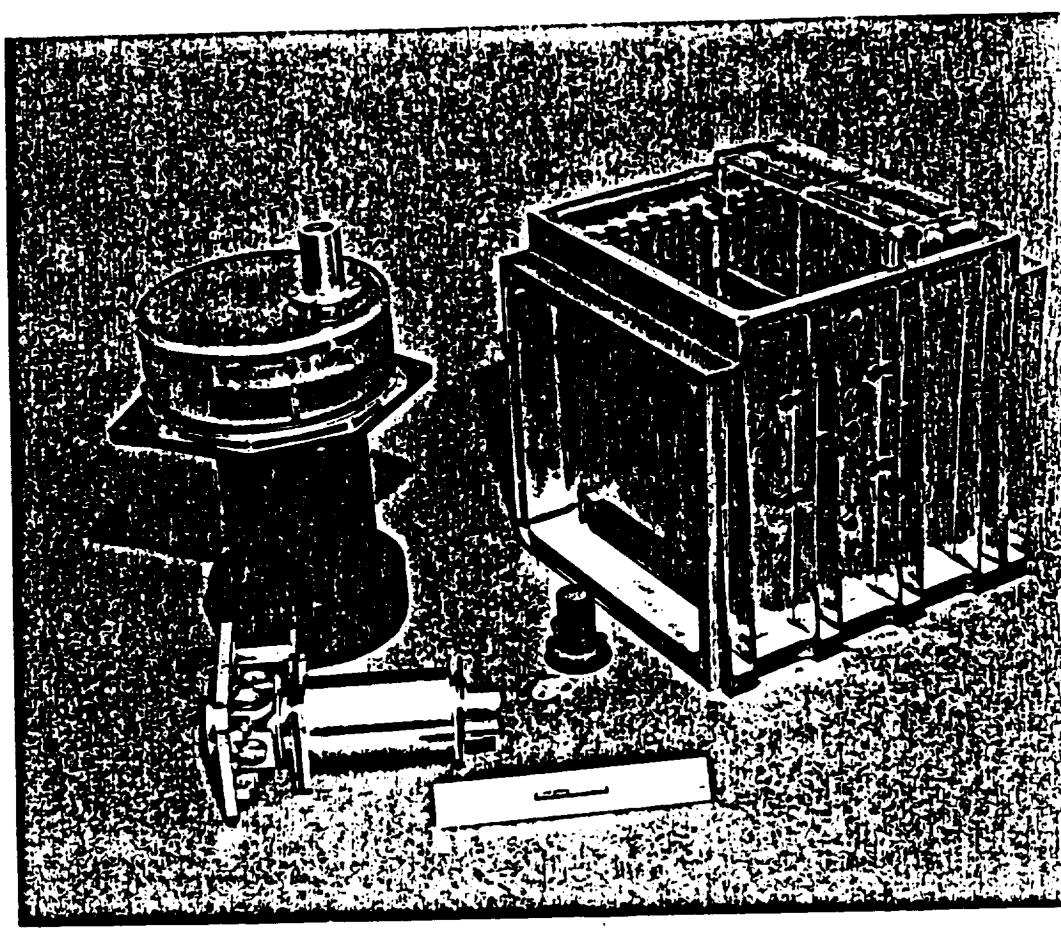
STATUS

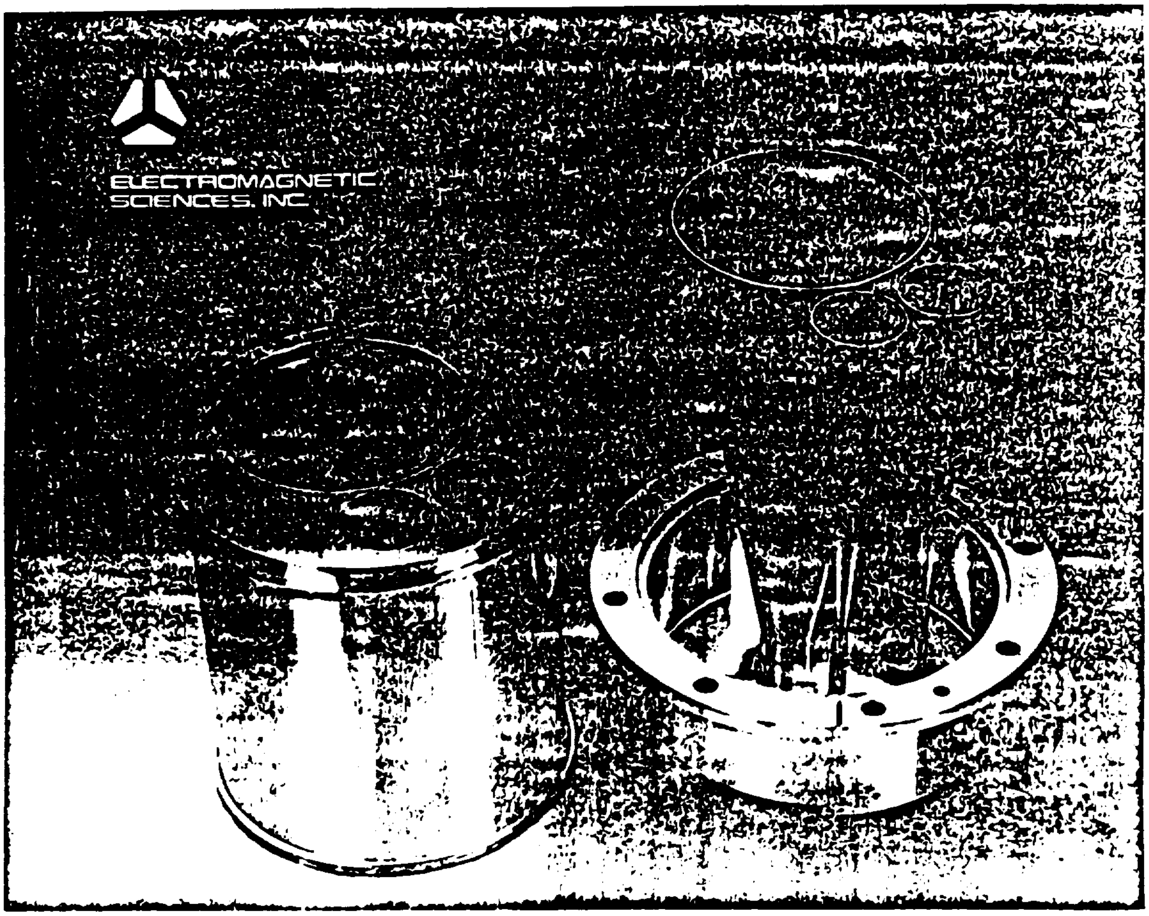
- PROGRAM
  - PROJECT REPLANNED TO ACCOMODATE 1991 AND 1992 FUNDING CONSTRAINTS
  - EMPHASIZE CARRIER VEHICLE DESIGN COMPLETION AND EXPERIMENT DEVELOPMENT
  - LAUNCH PLANNED FOR JULY 1996
- CARRIER VEHICLE
  - COMPLETED REVIEW OF NASA DESIGN - OCTOBER 1990
  - DESIGN TRANSFERRED TO CONTRACTOR - FEBRUARY 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

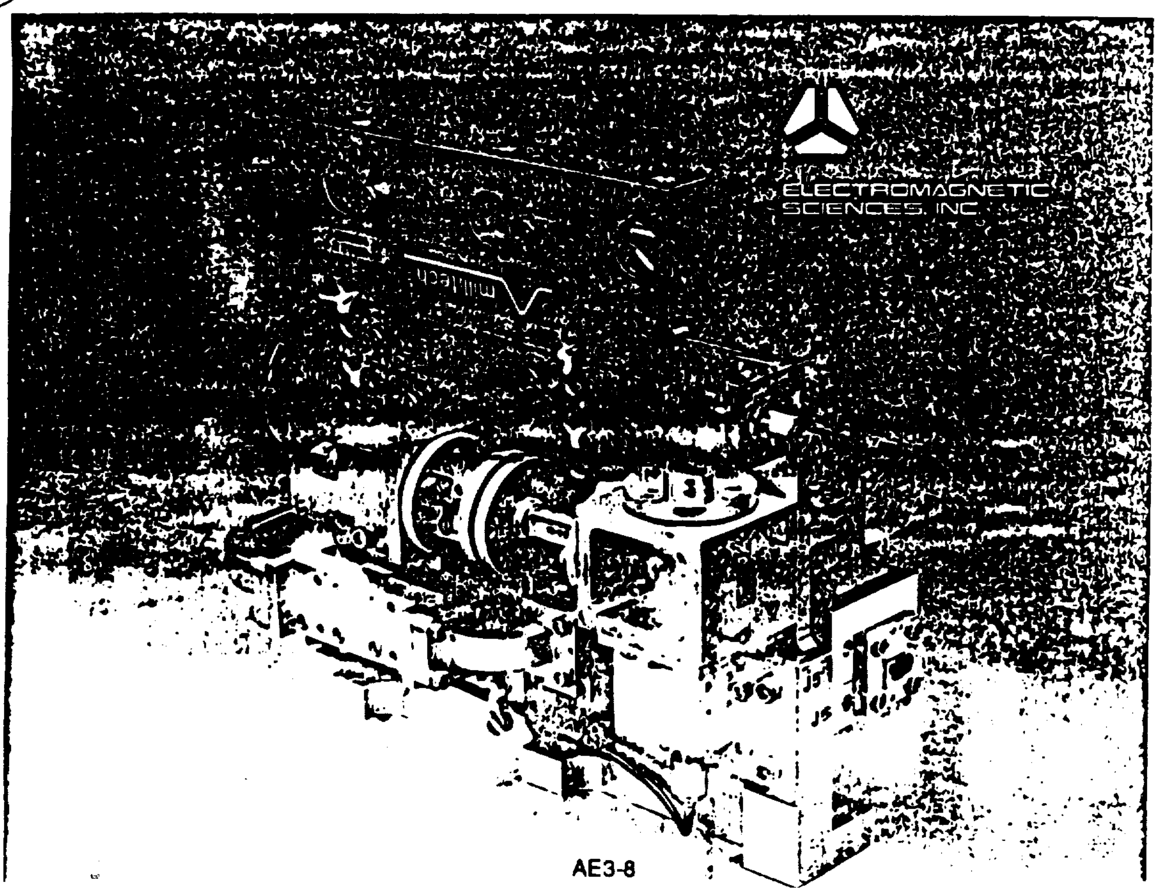


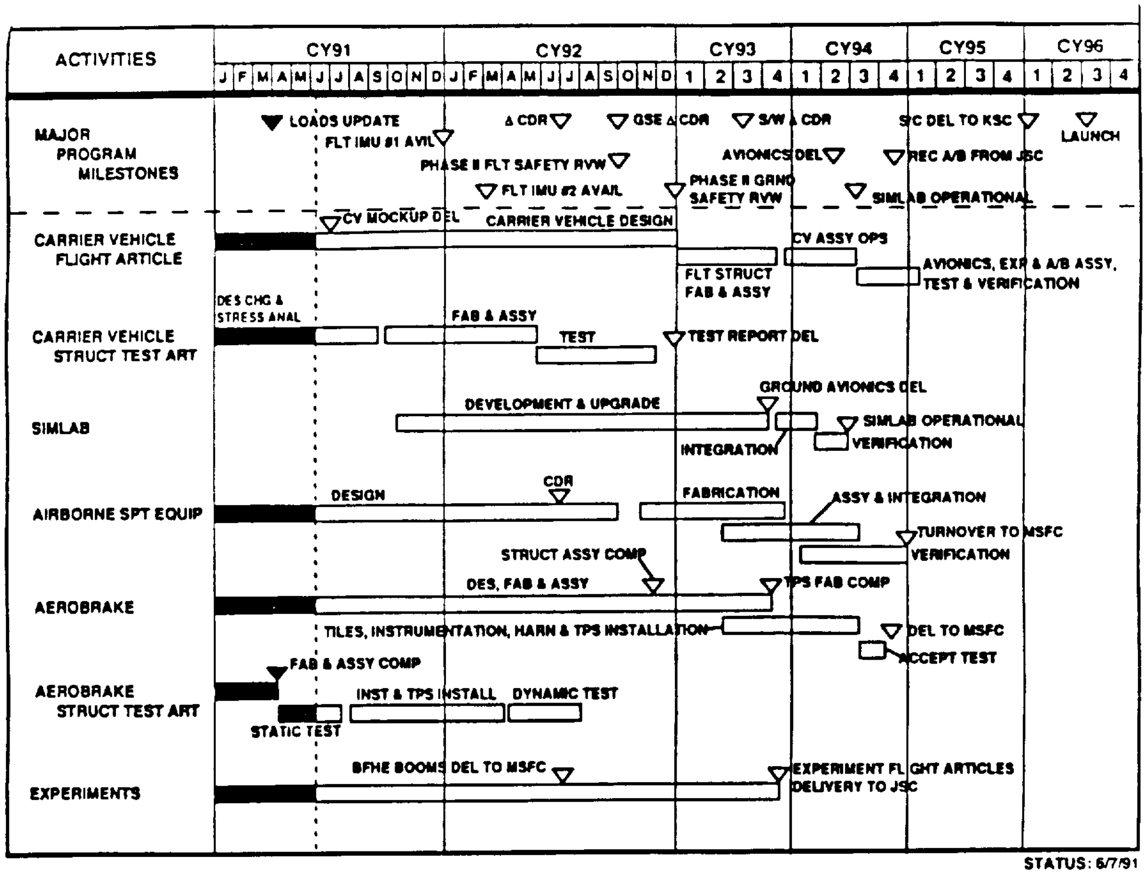
STATUS

- EXPERIMENTS
  - 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

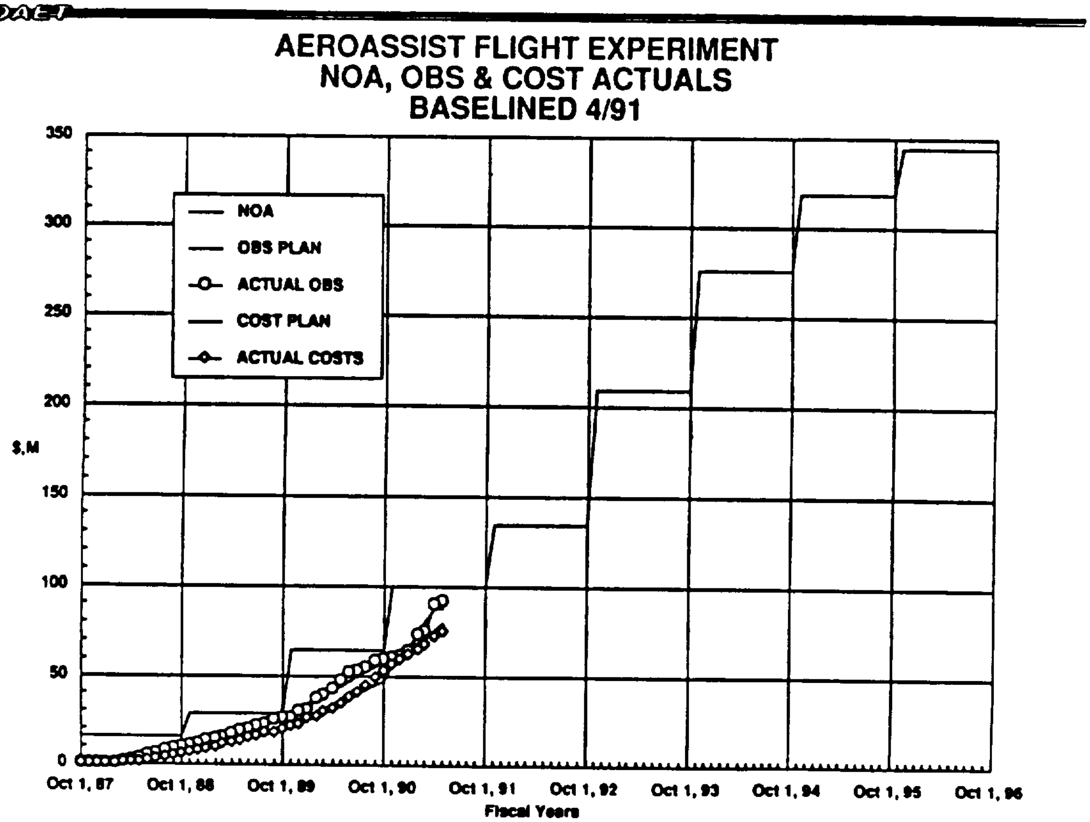



ELECTROMAGNETIC
SCIENCES, INC.


ELECTROMAGNETIC
SCIENCES, INC.


ACTIVITIES
CY91
CY92
CY93
CY94
CY95
CY96
MAJOR PROGRAM MILESTONES
LOADS UPDATE
FLT IMU #1 AVIL
CDR
GSE
CDR
S/W
CDR
S/C DEL TO KSC
LAUNCH
PHASE II FLT SAFETY RVW
AVIONICS DEL
REC A/B FROM JSC
FLT IMU #2 AVAIL
PHASE II GRND SAFETY RVW
SIMLAB OPERATIONAL
CARRIER VEHICLE FLIGHT ARTICLE
CV MOCKUP DEL
CARRIER VEHICLE DESIGN
CV ASSY OPS
FLT STRUCT FAB & ASSY
AVIONICS, EXP & A/B ASSY, TEST & VERIFICATION
CARRIER VEHICLE STRUCT TEST ART
DES CHG & STRESS ANAL
FAB & ASSY
TEST
TEST REPORT DEL
SIMLAB
GROUND AVIONICS DEL
DEVELOPMENT & UPGRADE
SIMLAB OPERATIONAL
INTEGRATION
VERIFICATION
AIRBORNE SPT EQUIP
CDR
DESIGN
FABRICATION
ASSY & INTEGRATION
TURNOVER TO MSFC
VERIFICATION
AEROBRAKE
STRUCT ASSY COMP
DES, FAB & ASSY
TPS FAB COMP
TILES, INSTRUMENTATION, HARN & TPS INSTALLATION
DEL TO MSFC
ACCEPT TEST
AEROBRAKE STRUCT TEST ART
FAB & ASSY COMP
INST & TPS INSTALL
DYNAMIC TEST
STATIC TEST
EXPERIMENTS
BFHE BOOMS DEL TO MSFC
EXPERIMENT FLIGHT ARTICLES DELIVERY TO JSC
STATUS: 6/7/91

AFE STATUS


AEROASSIST FLIGHT EXPERIMENT
NOA, OBS & COST ACTUALS
BASELINED 4/91
NOA
OBS PLAN
ACTUAL OBS
COST PLAN
ACTUAL COSTS
$,M
350
300
250
200
150
100
50
0
Oct 1, 87
Oct 1, 88
Oct 1, 89
Oct 1, 90
Oct 1, 91
Oct 1, 92
Oct 1, 93
Oct 1, 94
Oct 1, 95
Oct 1, 96
Fiscal Years

AEROASSIST FLIGHT EXPERIMENT

OAET

- 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

OAET

- 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 PROGESS 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

✓ Entry Technology Requir...

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 SURVIABILITY - 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: SOUNDING 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

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 F 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

✓ Entry Technology Required

- 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 AEROBRAKING 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

✓ Entry Technology Requir

- 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

	FY94	FY95	FY96	FY97	FY98	FY99
AEROTHERMODYNAMICS	.20	.50	.60	.60	.50	.30
GN&C	.20	.30	.60	.30	.30	—
STRUCTURES	.20	.50	.60	.60	.50	.50
THERMAL PROTECTION MATERIALS	.20	.50	.60	.60	.50	.50
	.80	1.80	2.40	2.10	1.80	1.30

APPROACH

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

- MARS PRECURSOR MISSIONS

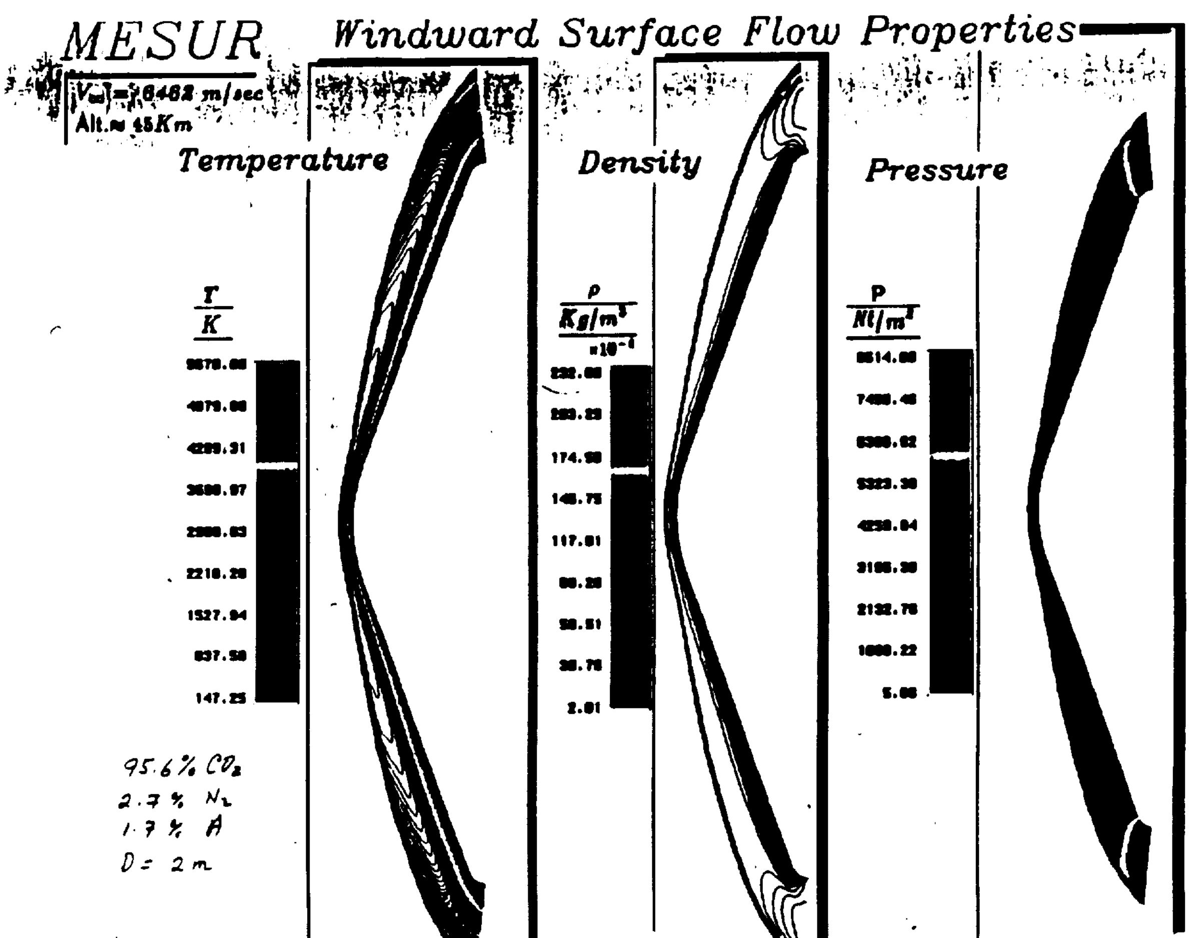
  MESURE
  MRSR

- OUTER PLANET ENTRY

  NEPTUNE PROBE

- HIGH SPEED EARTH RETURN

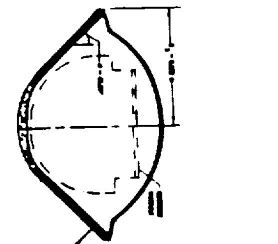
  COMET SAMPLE RETURN
  RTG PROBLEM

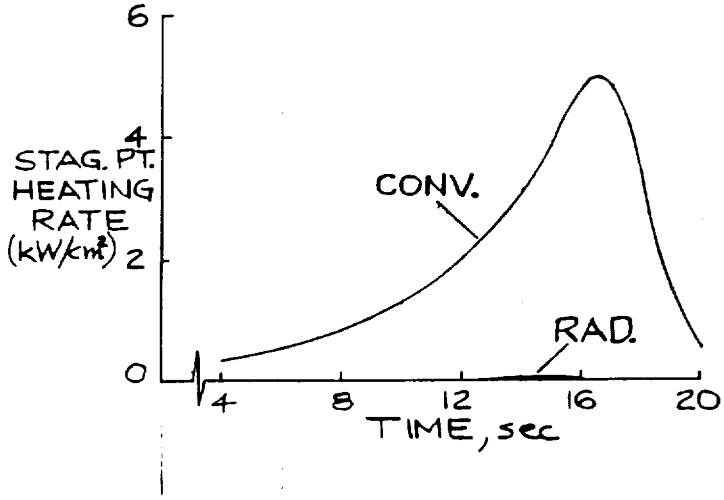


NEPTUNE PROBE "COLD WALL" HEATING RATES

$V_E = 25$ km/sec

$\gamma_E = -50°$





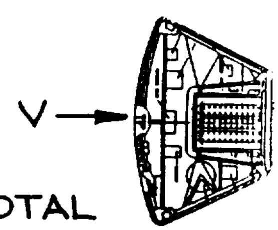
TAUE
6/7/

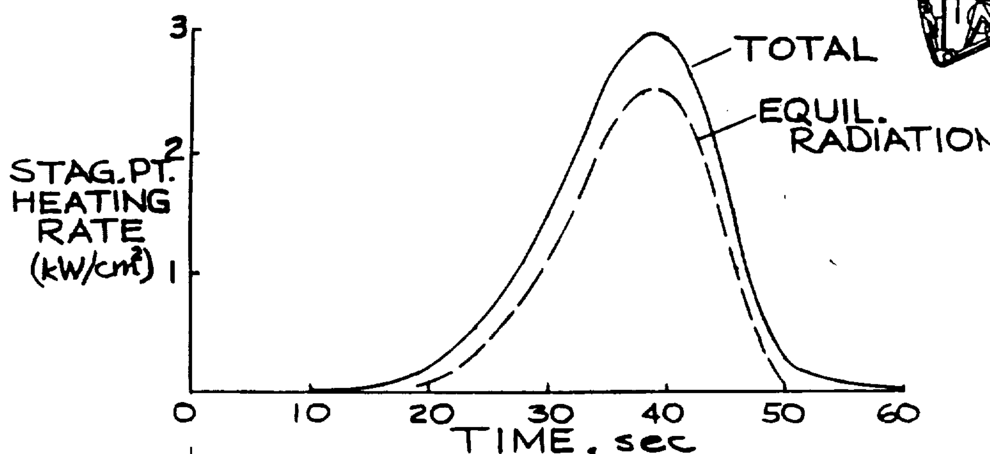
COMET SAMPLE RETURN VEHICLE "COLD WALL" HEATING RATES

$V_E = 15.5$ km/sec

$\gamma_E = -8°$

D = 1.85 m





TA

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.

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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**

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A&R PROGRAM OBJECTIVES

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

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MACHINE INTELLIGENCE (A&R)

COGNITION

- SENSATION
- PERCEPTION
- MEMORY
- PROBLEM SOLVING

↓

- PLANNING & SCHEDULING
- FAULT DIAGNOSIS
- DATA INTERPRETAION

IMPLEMENTATION

- MANIPULATION
- LOCOMOTION

↓

- SERVICING
- ASSEMBLY
- REPAIR

↓

- MISSION OPERATION
- TELESCIENCE
- SATELLITE SERVICING
- REMOTE EXPLORATION

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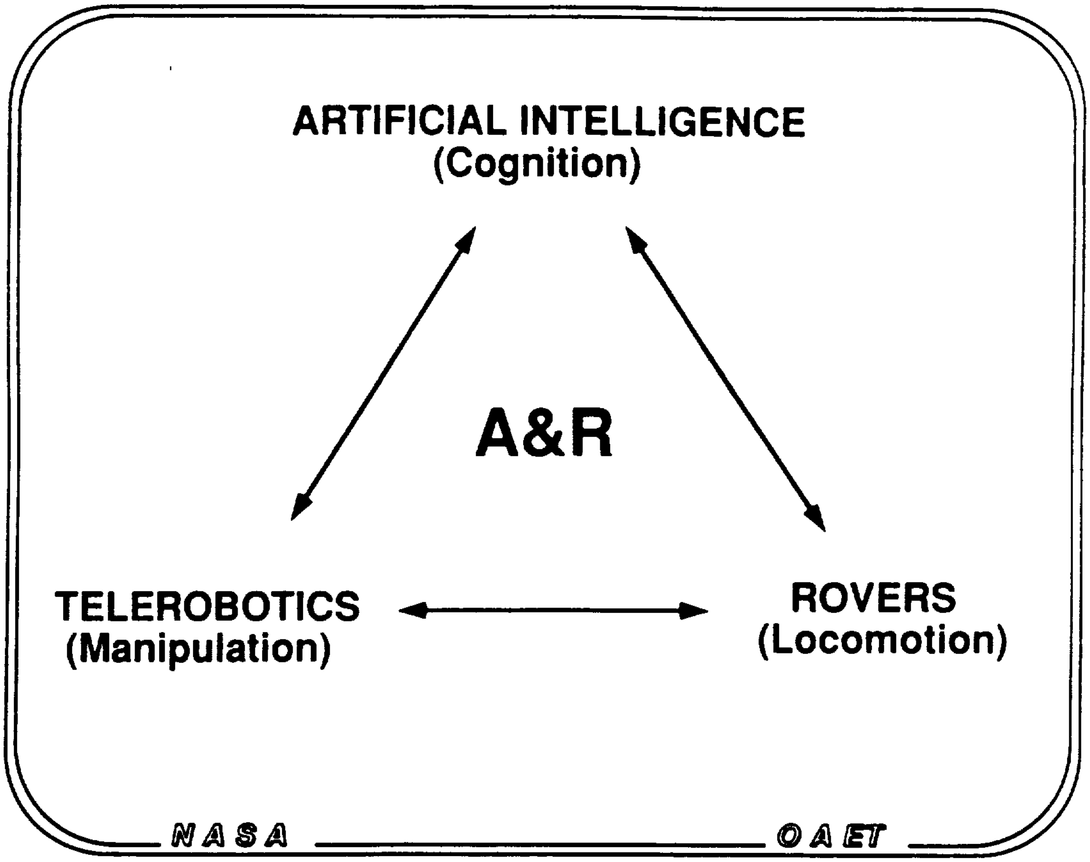

A&R NEEDS/OPPORTUNITIES

	TR	A.I.	ROVERS
IN-SPACE	- EVA servicing & assembly - Cranes - IVA processing	- Health monitoring and maintenance - Process control - Data interpretation - Training	- Free-flyers (eg OMV) (eg EVA retriever)
TERRESTRIAL	- Manufacturing - STS processing - Satellite inspect.	- Mission Control - Data analysis - Planning & Sched - NASA Infrastructure - Design	- Emergency response vehicle - STS tile waterproofing
PLANETARY	- assy, servicing - science ops	- Systems autonomy	- Science - Transportation - Construction

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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

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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*

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A&R TECHNOLOGIES

TELEROBOTICS	ARTIFICIAL INTELLIGENCE	ROVERS
- Control - Human Interface - Sensing & Perception - Intelligence - Mechanisms - Architecture - Processors - Systems Integration - Implementation Infrastructure	- Planning & Scheduling - Learning - Large Knowledge Bases - Knowledge Rep. - Model-based Reasoning - Human Interface - Diagnosis - Real-time Control - Validation & Verification - Systems Integration	- Mobility - Navigation - Vision - Power - Autonomy - Processors - Payload(SAAP) - Sys. Integration

SYNERGISM

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

1980 1984 1988 1991

1980
- TRADITIONAL AUTOMATION ONLY
- OAST TAKES FIRST STEPS IN A&R

1984
- 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

1988
- 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 $

1991
- 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

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A&R FUNDING ($M)

	1984	1985	1986	1987	1988	1989	1990	1991	1992
AI & TR	4.5	8.2	10.2	17.8	25.3	25.8	21.4	22.7	27.9
ROVER						5.0	2.8	3.0	0.0**
R&T BASE									0.8

** ROVER FUNDING IN FY92 INCLUDES $0.8M IN R&T BASE AND $0.75M IN TELEROBOTICS

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ARTIFICIAL INTELLIGENCE

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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.

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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.

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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

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AI: 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-independant 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 realtime scheduling for Shuttle processing,
- Use of massively parallel processors to amplify AI capabilities
- Widespread use of AI in NASA infrastructure (eg 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 data-bases
- Data visualization tools used for scientific & engineering analyses

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AI PROGRAM: Tasks

Intelligent Assistance for Mission Operation	Center
- Automated Scheduling Tools	ARC
- Advanced Interaction Media	ARC
- SHARP	JPL
- RTDS	JSC
- Guidelines: Human Interface with AI	JSC
- EXODUS Shell	KSC
- KATE - LOX	KSC
- Ops. Mission Planner	JPL
- Proc. Reas. Sys (PRS) for Shuttle Mission Cntr.	JSC
- AI for Software engineering	ARC,JPL,JSC
- Shuttle Ground Processing Scheduling	ARC, KSC
Scientific and Engineering Data Analysis Techniques:	
- P.I. in a Box	ARC
- Automatic Classification and Theory Formation	ARC
- Scientific Analysis Assistant	JPL
- NASA Infrastructure Expert Systems	
- PC-based scheduler	JSC
- ADPE planning expert system	JPL
- Intelligent Purchase Request system	ARC

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AI PROGRAM: Tasks (continued)

Autonomous Control:	
- DTA-GC Instrument Control System	ARC
- Intelligent Interacting agents	ARC
- Integration of Symbolic and Numeric Control	ARC
- Machine Learning for Sys. Maint. & Improvement	ARC
- Predictive Monitoring	JPL
- Space Station Power Expert System	LeRC
- F[illegible]D (Power) Cooperative Expert System	MSFC
- Diagnosis of Physical Systems	ARC
Knowledge Base Technology:	
- Large-Scale Knowledge Base	ARC
- Knowledge Acquisition & Use During Design	ARC
- Distributed Knowledge Base Management	GSFC

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AI Program ($M)

HISTORY

1984	1985	1986	1987	1988	1989	1990	1991	1992
2.3	4.1	4.9	8.8	12.0	11.1	10.9	10.7	13.1

PROPOSED	1993	1994	1995	1996	1997
Baseline	13.9	14.2	14.9	15.6	16.6
Constrained	13.9	16.5	18.7	20.1	22.3
Strategic	15.9	19.7	23.8	26.7	30.3

IMPLICATIONS

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

* - assuming low inflation rate

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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.

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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 MIMIMUM 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

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TELEROBOTICS

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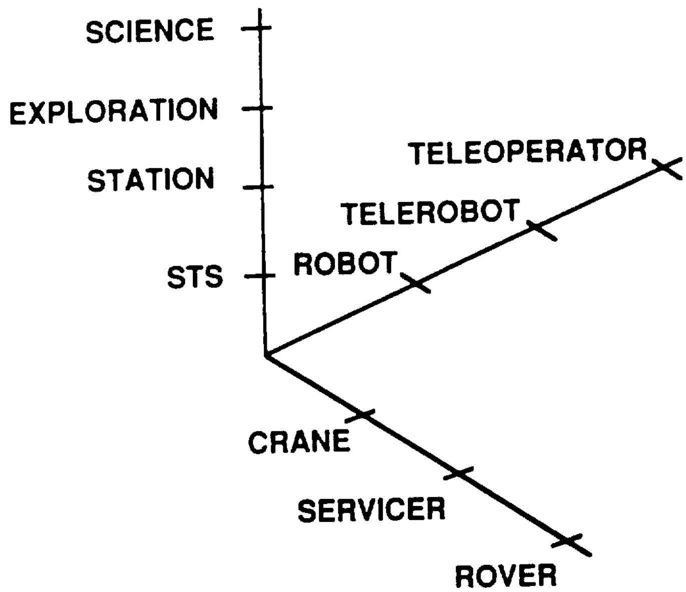
NEEDS/OPPORTUNITIES MATRIX



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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

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SPACE TELEROBOT SPECTRUM

TYPES OF TELEROBOTS	*ENVIRONMENT* ON-ORBIT	TERRESTRIAL	MOON/MARS
SERVICERS	- FTS - SPDM	-VACUUM PLASMA SPRAY ROBOT FOR SME	- EXOSKELETON FOR SITE MAINTENANCE
CRANES	- STS RMS - SSF RMS - VEHICLE ASSY	- ORBITER / 747 MATE/DEMATE DEVICE	- LUNAR VEHICLE UNLOADER (LEVPU)
MOBILE ROBOTS	- OMV - ETS-7	- STS TILE INSPECTION	-UNMANNED & MANNED ROVERS
SPECIAL PURPOSE DEVICES	- NODE &STRUT ASS'Y	- STS PCR FILTER INSPECTION	- LUNAR TUNNEL DIGGER - MICROROVER SOIL SAMPLER

TELEROBOTICS BENEFITS

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

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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

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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

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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 Rensselear 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

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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

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TELEROBOTICS PROGRAM

I N SPACE

	Center	Challenge
Teleoperations:		
- Cranes	JSC	8,7,1
- Advanced Teleoperation	JPL	8,1,2
- Free-flying manipulators	U. MD.	7,3,1
- Exoskeletons	JPL	1,8,4
Telerobotics (Supervisory Control		
- Telerobotic Inspection	JPL	8,1,2
- Compound Manipulators	LaRC	8,4
Robotics:		
- Structural Assembly	LaRC	4,1
- Multiple Autonomous Robots (Stanford)	ARC	7,8
- Fault Tolerant Actuators (Univ of Texas)	JSC	7,5,8
- Servicer Automation	GSFC	1,4

GROUND

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

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TELEROBOTICS: PROGRAM ACCOMPLISHMENTS

	CHALLENGE
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

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TELEROBOTICS: "LEVEL 0" MILESTONES

		CHALLENGE
1991	EMERGENCY RESPONSE VEHICLE	6
1992	COOP MANIPULATION FOR FREE-FLYING TELEROBOTS	1,7
1992	TELEOPERATED DEMO OF SOLAR MAX REPAIR	8,3,1
1992	HEPA FILTER INSPECTION ROBOT FOR PCR AT KSC	6
1993	AUTOMATED ASSEMBLY OF NON-PLANER STRUCTURE	4,5,2
1993	MULTI-SENSOR ROBOT INSPECTION FOR GAS LEAKS,ETC	6
1994	ROBOTIC PLASMA SPRAY GUN FOR SSME COMBUSTION CHAMBER FABRICATION	6,8
1994	SHUTTLE TILE INSPECTION & WATERPROOFING ROBOT	6,8
1994	DUAL-ACTUATOR WITH REDUNDANT MOTORS, ENCODERS, GEAR TRAINS.	5,8
1995	EXOSKELETON TELEPRESENCE SYSTEM	1,8
1996	PERFORM ROBOT ASSY OF SOLAR-DYNAMIC STRUCTURE	4,1

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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 WINS
  - 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

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INTEGRATION OF A ROBOT INTO A SYSTEM

INTEGRATION OF COMPONENTS INTO A ROBOT

COMPONENT DEVELOPMENT

- CONTROLS
- SENSORS
- MECHANISMS
- INTELLIGENCE
- HUMAN INTERFACE
- ELECTRONICS
- PROCESSORS
- POWER
- ARCHITECTURE

COMPONENT

- SELECTION
- MODIFICATION
- INTEGRATION

OPTIMIZE ROBOT PERFORMANCE

- ADAPT SYSTEM
- ADAPT EQUIPMENT
- ADAPT PROCEDURES
- ADAPT ROBOT DESIGN

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

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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; dont design first for evolution)
  (minimize development time)
- Invest for long term payback to research

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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
- PERC[illegible]ON THAT SPACE TELEROBOT WILL COST OVER $1B
- FAIL[illegible]NY TELEROBOTICS DEMONSTRATIONS
- LACK OF RO[illegible]ICISTS 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 QUADRUPLINGS

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TR Program ($M)

HISTORY

1984	1985	1986	1987	1988	1989	1990	1991	1992
2.3	4.1	5.3	8.9	13.0	13.3	10.9	11.6	14.6

PROPOSED	1993	1994	1995	1996	1997
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

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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.

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TELEROBOTICS: Conclusions

NEAR TERM OBJECTIVES:
- **STAY ALIVE**
- **CREATE A MARKET**

- It is imperative that the Code RC TR program continue in existance 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 telerobotics.

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A&R CONCLUSIONS AND RECOMMENDATIONS

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TWO IMPORTANT OPEN ISSUES

- Space Station
- Space Exploration Initiative

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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

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A&R PROPOSED FUNDING PROFILES ($M)

	91	92	93	94	95	96	97
ARTIFICIAL INT.							
- Baseline	11.2	13.1	9.9	10.2	10.9	11.6	12.3
- Constrained	11.2	13.1	9.9	10.2	10.9	11.6	12.3
- Strategic	11.2	13.1	11.9	12.7	14.8	16.9	18.3
TELEROBOTICS							
- Baseline	11.0	14.8	12.4	12.8	13.6	14.3	15.1
- Constrained	11.0	14.8	12.4	12.8	13.6	14.3	15.1
- Strategic	11.0	14.8	12.4	12.8	18.1	23.4	30.3
A.I. R&T BASE							
- Baseline	0	0	4.0	4.0	4.0	4.0	4.0
- Constrained	0	0	4.0	6.3	7.8	8.5	10.0
- Strategic	0	0	4.0	7.0	9.0	10.0	12.0
TR R&T BASE							
- Baseline	0	0.8	3.8	3.8	3.8	3.8	3.8
- Constrained	0	0.8	3.8	6.1	6.8	7.3	9.8
- Strategic	0	0.8	3.8	6.8	7.8	9.8	11.8
ROVERS							
- Baseline	3.0	0	0	0	0	0	0
- Constrained	3.0	0	5.0	8.1	8.5	9.0	12.0
- Strategic	3.0	0	5.3	13.4	17.6	24.5	30.1
FTS DTF							
- Baseline		55.0	75.0	40.0			
- Constrained		55.0	75.0	40.0			
- Strategic		55.0	75.0	40.0			

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A&R - three proposals

	BASELINE	CONSTRAINED	STRATEGIC
OPERATIONS - artificial intelligence - telerobotics	- Focussed AI - Focussed TR	SAME AS BASELINE	-small augs in 93-95 -large augs in 96-97
R&T BASE - artificial intelligence - telerobotics	-portion of AI & TR moved to R&T Base in FY93	AI & TR AUGMENTED	SAME AS CONSTRAINED,BUT LARGER AUG.
EXPLORATION - rovers	-funding ends in FY91	Science rover funding reinstituted in FY93	Augmented to add manned rover in FY94
TECH FLT EXPT	- DTF-1 under Code RX	SAME AS BASELINE	SAME AS BASELINE

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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 ADOLESENCE, 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 IMMENDIATE NEED TO SEEK NEAR TERM TO STAY ALIVE
- NEEDS EXPERTISE IN ROBOT SUSTEM IMPLEMENTATION

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

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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

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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

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PUBLIC LAW 98-371 NASA R&D, 98 Stat. 1227. (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."

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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 alow 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

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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.

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National Commission on Space "Pioneering the Space Frontier"

"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-recognizing automata is needed. They must employ new computers, sensors and diagnostic and maintenance equipment that can aviod 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."

NASA ——— *OAET*

National Commission on Space "Pioneering the Space Frontier"

"Robo[illegible] human exploration and surveying of substantial areas of the [illegible] Mars. This effort will begin on the Moon with autom[illegible] vehicles teloeperated from Earth, and on Mars with vehic[illegible] substantial artificial intelligence. Robots will be followed [illegible] first astronaut crews operating from Lunar and Martian outpos[illegible] bases."

NASA ——— *OAET*

ORIGINAL PAGE IS OF POOR QUALITY

Leadership & America's Future in Space: the Sally Ride Report

Concerning Mars sample return:
"As it is defined, this initiative places a premium on advonced technology and enhanced launch capabilities to maximize the scientific return. It requires aerobraking trechnology 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 robotric exploration in the 1990s, this initiative would land astronauts on the lunar surface in th year 2000..... The initial phase would focus on robotic exploration of the Moon. ... Depending on the discoveries of the Observer, rovotic landers and rovers may be sent to the surface to obtain more information.

Concerning the Mars Exploration initiative:
" This iniative 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.

NASA OAET

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 requirments 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 brethern. Then 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, repititious 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 manpulators 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."

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Space Technology to Meet Future Needs: an ASEB report

Chapter 8

Automation, Robotics and Autonomous Systems

Pages 78 to 85

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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 so central to success that their underlying technology took its place beside the other, traditional technologies. Today this 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 in-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 fuels 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

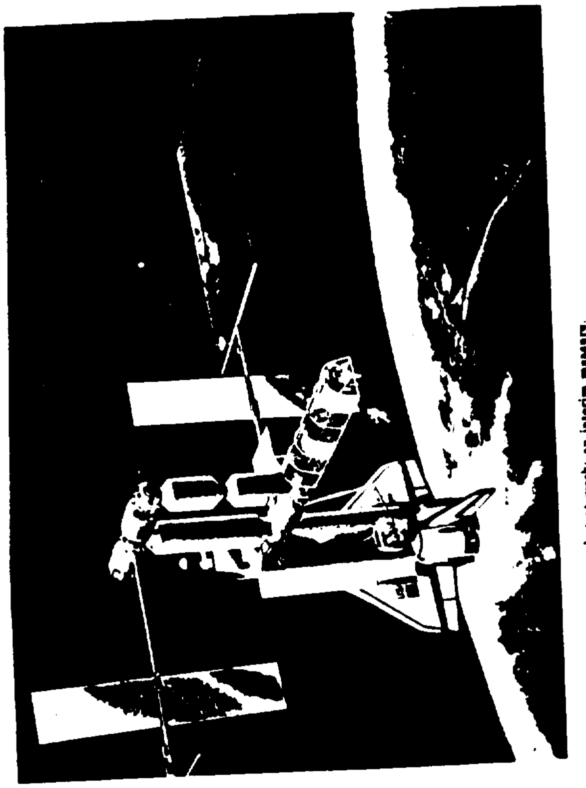

FIGURE 9 Surrogate space robot at work: an interim measure.

can enhance astronaut effectiveness to the utmost. Each human must be free of mundane and repetitious tasks—of mind or hand—so that the unique judgment and dexterity that only humans possess are optimized. 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, limber, 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 computers 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 $25 million a year starting in FY 1988).

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 Land Vehicle (ALV) program and some Army programs.

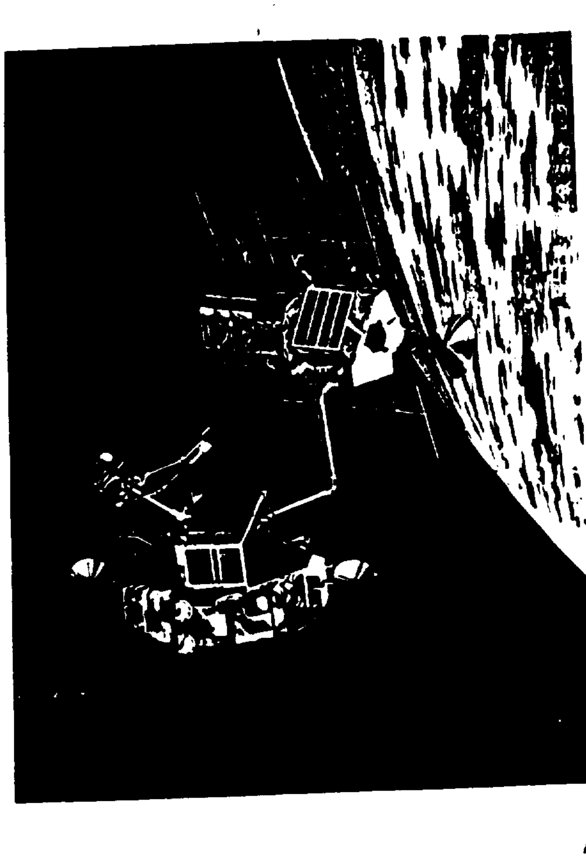

FIGURE 10 Current space robot concept; orbital maneuvering vehicle with manipulative capability.

In 1985 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, minimium-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 $190 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 these 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 to which the NASA program must be directed. 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 mechanization 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 operation in the complex, uncertain, hazardous space environment (relative to factory robots that tend to perform 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 predeterminable, 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; this 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 is 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 no 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.

Increases in 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 space automation and robotics. "Demonstration" 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.

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

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

pages 33 to 35

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ARTIFICIAL INTELLIGENCE

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.

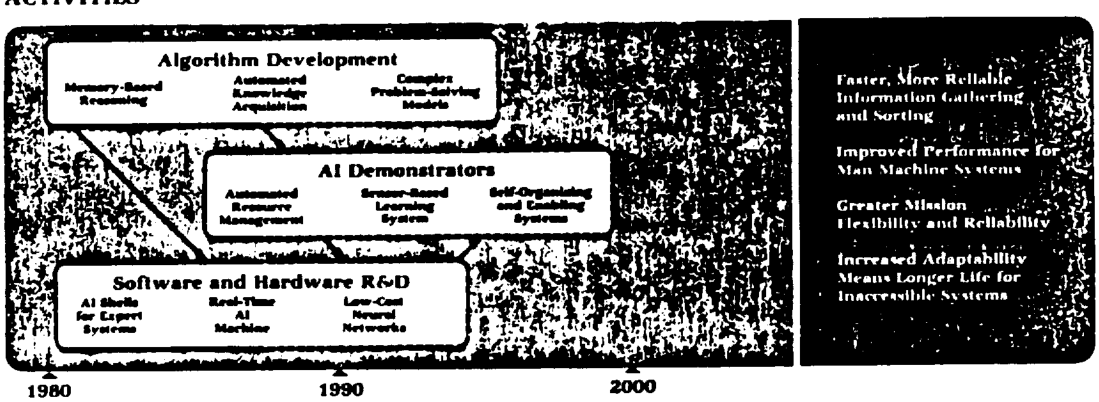
This advanced technology is concerned with complicated data processing problems and the development of problem-solving capabilities that elaborate on a model of human intelligence. AI covers a number of computer-based activities, one of the most common being the design of "expert" systems. Traditional computing techniques required hours of laborious programming to load a data base 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 only "learns" from new human input. Future AI systems will be capable of machine learning; their data bases 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.

ARTIFICIAL INTELLIGENCE

ACTIVITIES **PAYOFFS**



ADVANCEMENT INHIBITORS

- **Insufficient knowledge of human problem-solving process**
- **New AI technologies suffer from:**
  - Unpredictable performance
  - Lack of design tools that need to be developed and proven
  - Different risk perceptions between AI and system developers
  - Divergence between academic and nonacademic technology trends

REQUIRED DEVELOPMENT

- **Ultrareliable software validation methods for expert systems**
- **Advanced computer system for problem formulations, solution design and software design, development and maintenance**
- **Improved techniques for modeling and processing information contaminated by uncertainty**
- **Software capable of commonsense reasoning**

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

Application of artificial intelligence will result in revolutionary productivity improvements for man machine systems

	Applications				
	Vehicle	Sensors	Mission Support	Weapon Systems	Manufacturing
[illegible]	•	•	•	•	•
[illegible]	•			•	
[illegible]	•	•	•	•	
[illegible]	•	•		•	
[illegible]	•	•	•	•	•

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

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

"By the turn of the century, applications of AI are expected to revolutionizea 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 inaccessable systems**

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

NASA OAET

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 REPLENISHED
      - 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 persued which will enable a permanent, possibly man-tended outpost to be establised on the Moon for the purposes of exploration and for the development of the experience base requiremd for the eventual human exploration of Mars. That NASA should initiate sutdies of robotic precursor missions and lunar outposts.

NASA OAET

AUGUSTINE REPORT - Items onNASA 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

NASA OAET

AUGUSTINE REPORT - Items onNASA 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 Spacae Station that are or will be largely dirven by operational issues - turnaround time between flights, manifesting, retrofitting of design changes for safety, cost or payload capability purposes, logistics, training of gasic 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 ofexcellence

NASA OAET

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

NASA OAET

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

NASA OAET

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

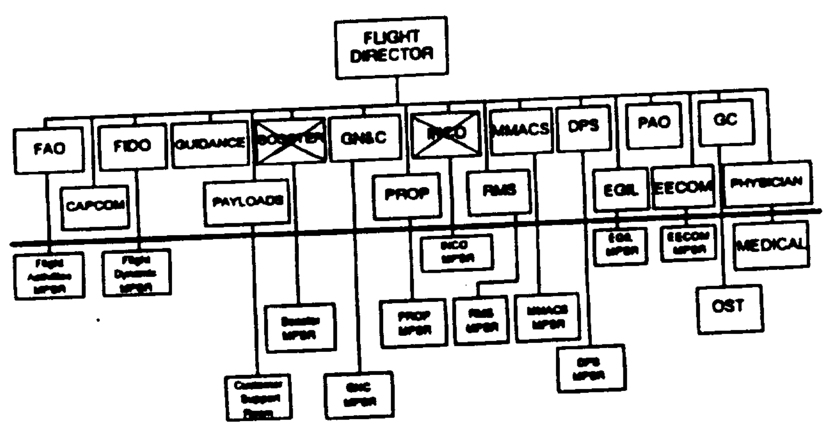
Goals

- Increase the quality of flight decision making
- Reduce/enhance flight controller training time
- Serve as a near-operations technology test-bed

2

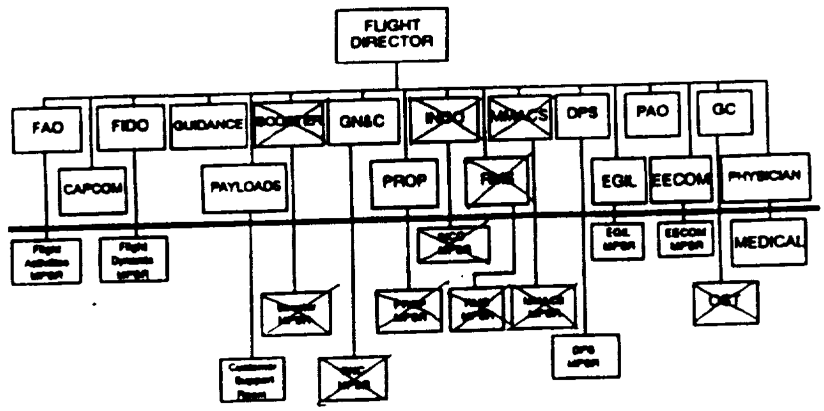
1987

Road Map of Flight Control Disciplines



1989

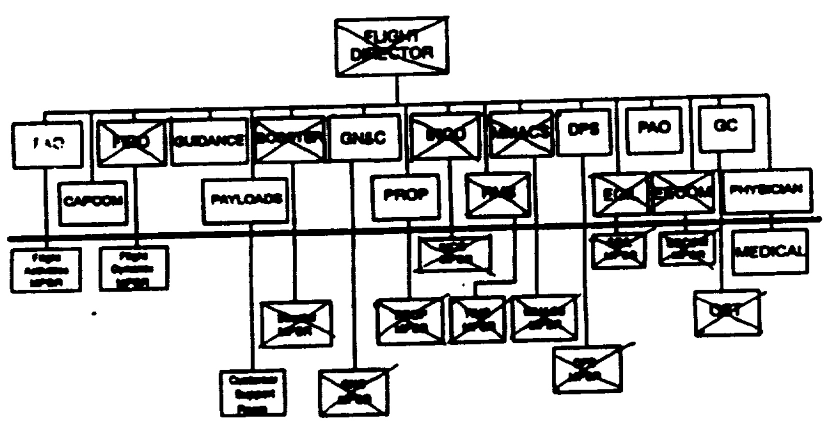
Road Map of Flight Control Disciplines



7

1991

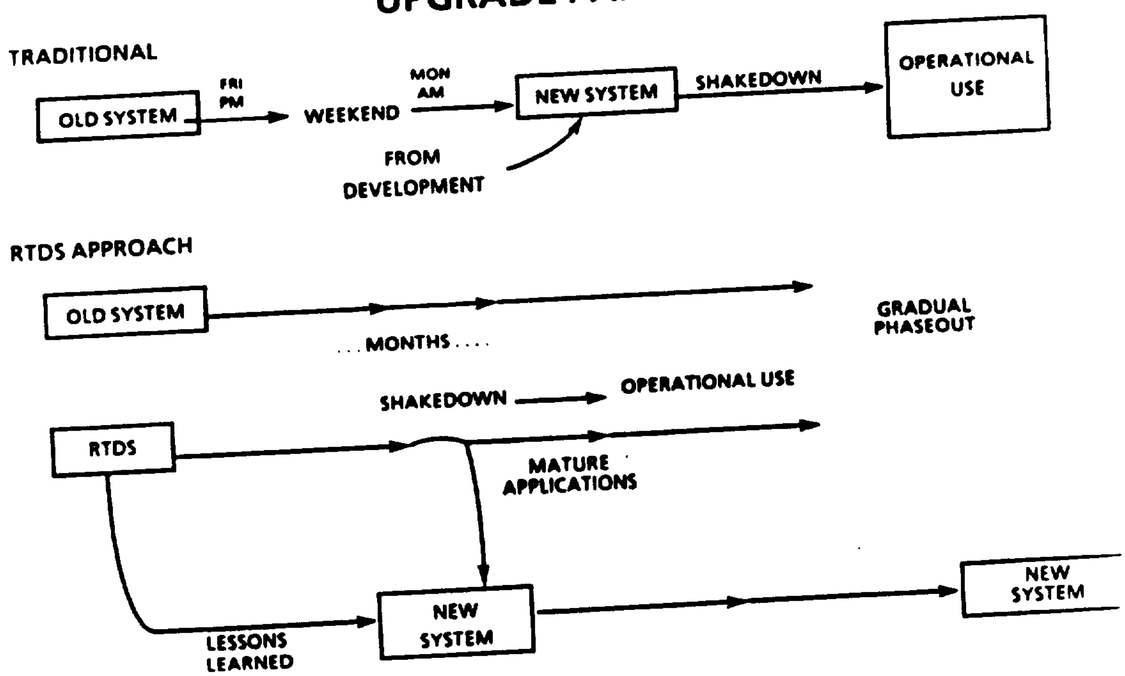
Road Map of Flight Control Disciplines



REAL TIME DATA SYSTEM (RTDS)

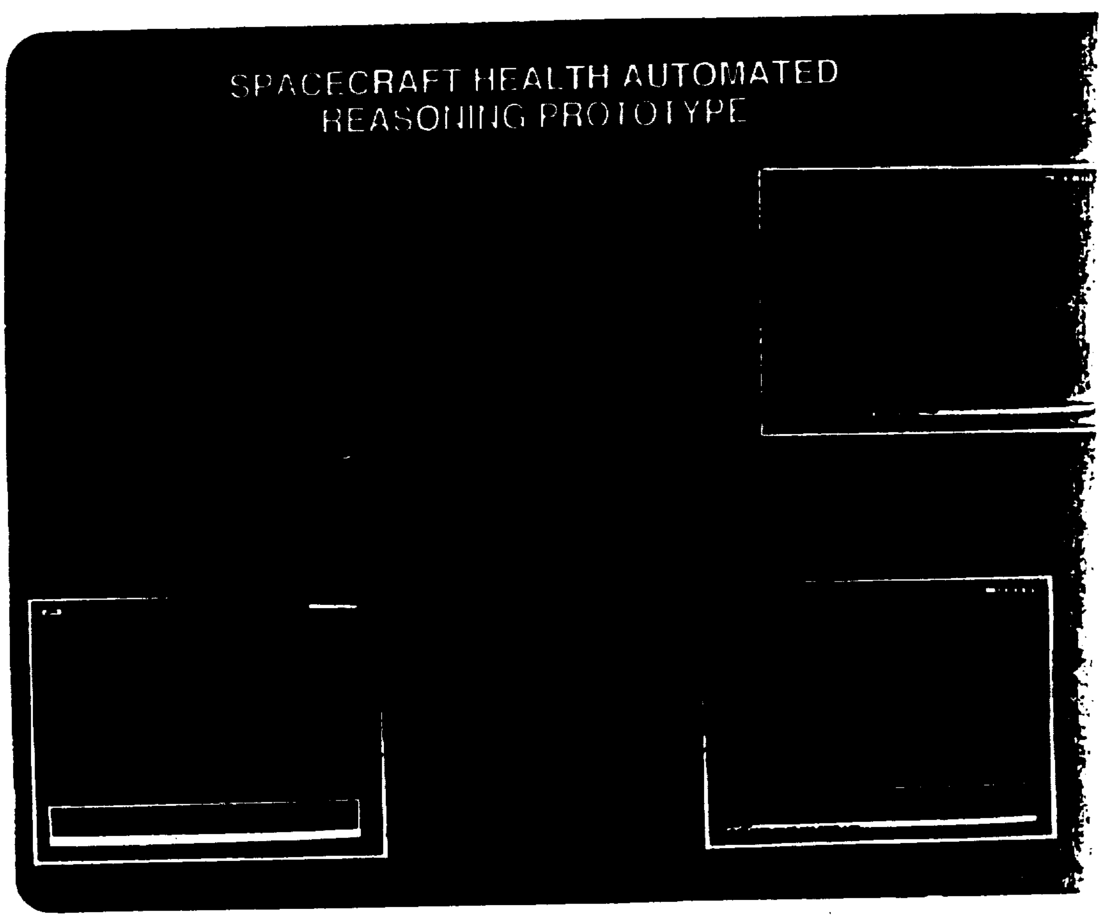
- FEB 89 - STS-29 RTDS EXPANDED TO INCLUDE:
  - TIRE PRESSURE AUTOMATED MONITORING
    - PREVIOUSLY REQUIRED FULL TIME PERSON TO ACQUIRE DATA, COMPENSATE FOR TEMPERATURE, CONVERT TO STANDARD PRES AND PLOT (TASK AUTOMATION)
  - VISUALIZATION OF FLIGHT INSTRUMENTS (TASK AUTOMATION)
  - ASCENT GNC MONITORING - (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



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



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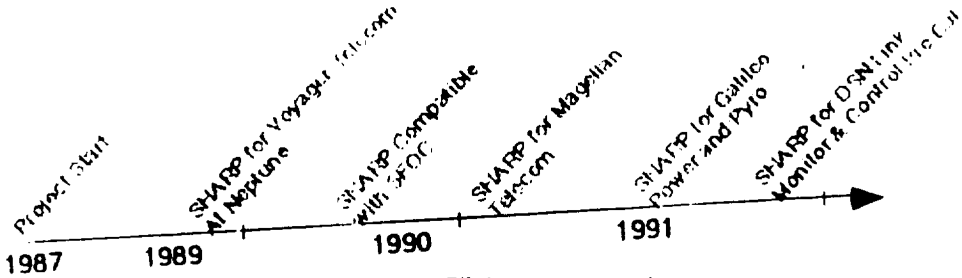
OF POOR QUALITY

SHARP PROGRESS



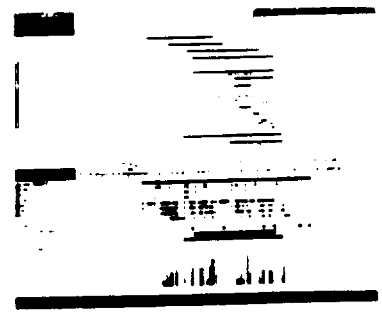
Evaluation Prototype	Reusable Kernel	Pilot Installation	*Underway*
Shallow Diagnosis	Constraint Based Diagnosis	Deeper Telecom Diagnosis	
30 Sec. to Diagnose	1.5 Sec. to Diagnose	"Anytime" Diagnosis	
Max - 100 RT Channels	Max - 10K RT Channels	Capacity to Spare	
LISP Machine	Sun and SFOC Compatible	Installed in Magellan Ops	

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

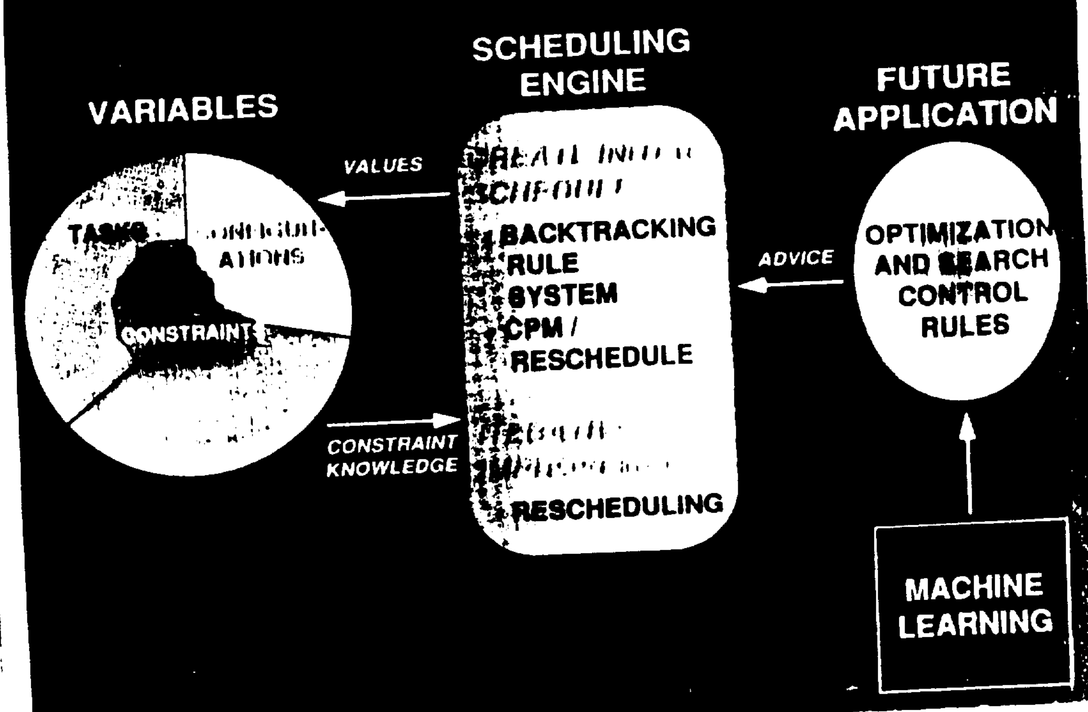
TRADITIONAL — SYSTEMATIC BACKTRACKING

- GUARANTEED TO TERMINATE
  - INTUITIVE
    - EXHAUSTIVELY TESTED

ITERATIVE IMPROVEMENT — SIMULATED ANNEALING

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

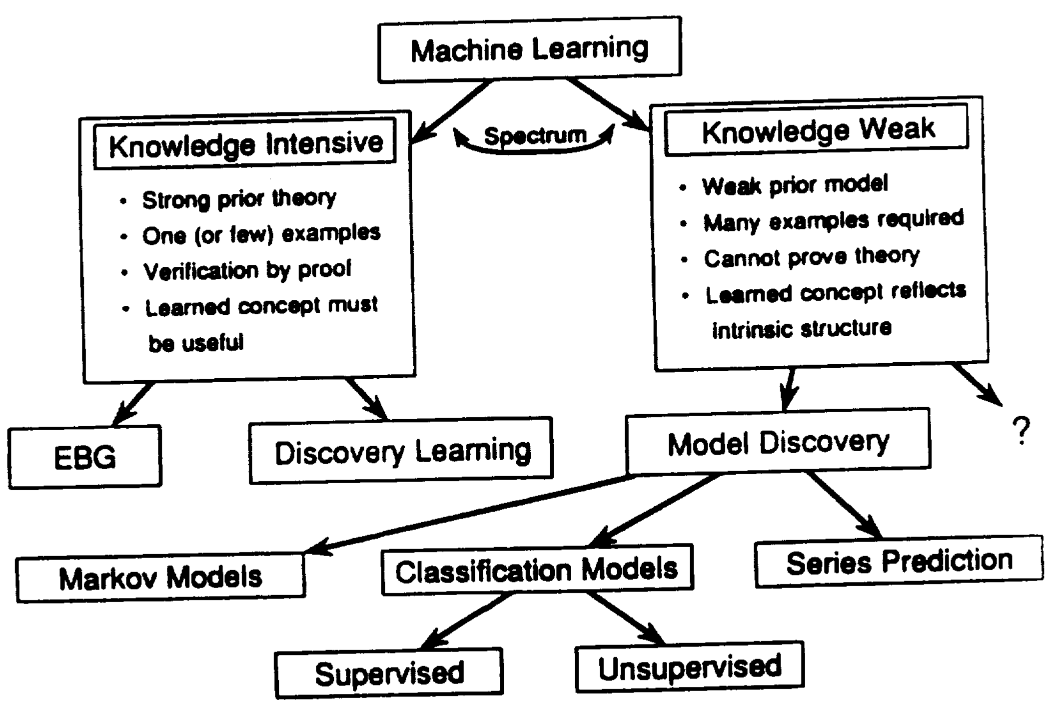
SYSTEM ARCHITECTURE

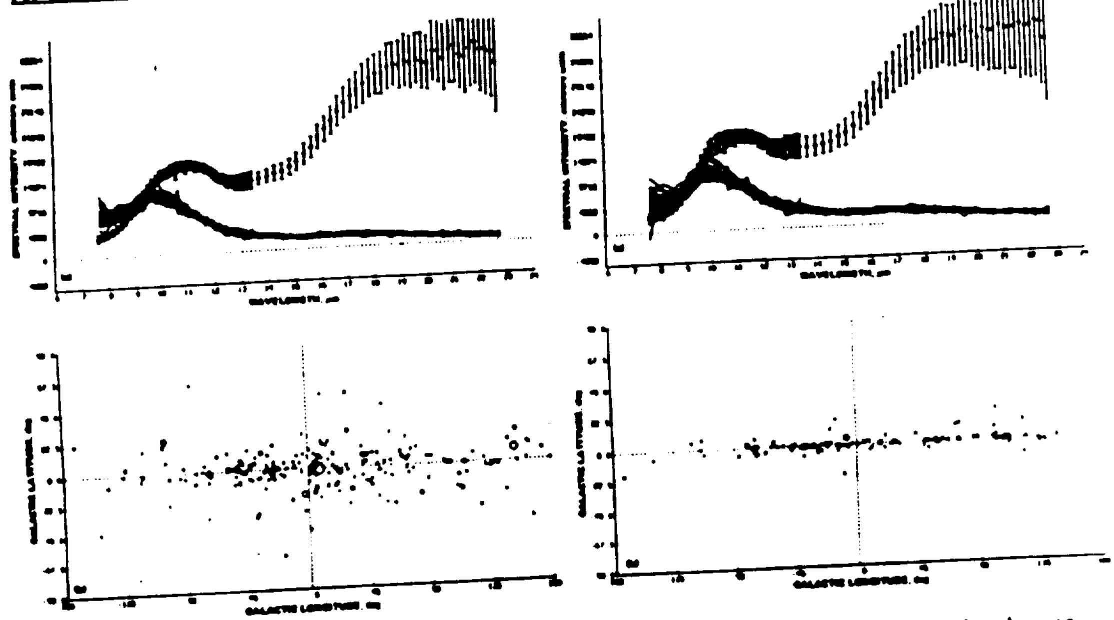


Bayesian Learning

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

NASA AUTOCLAS





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)

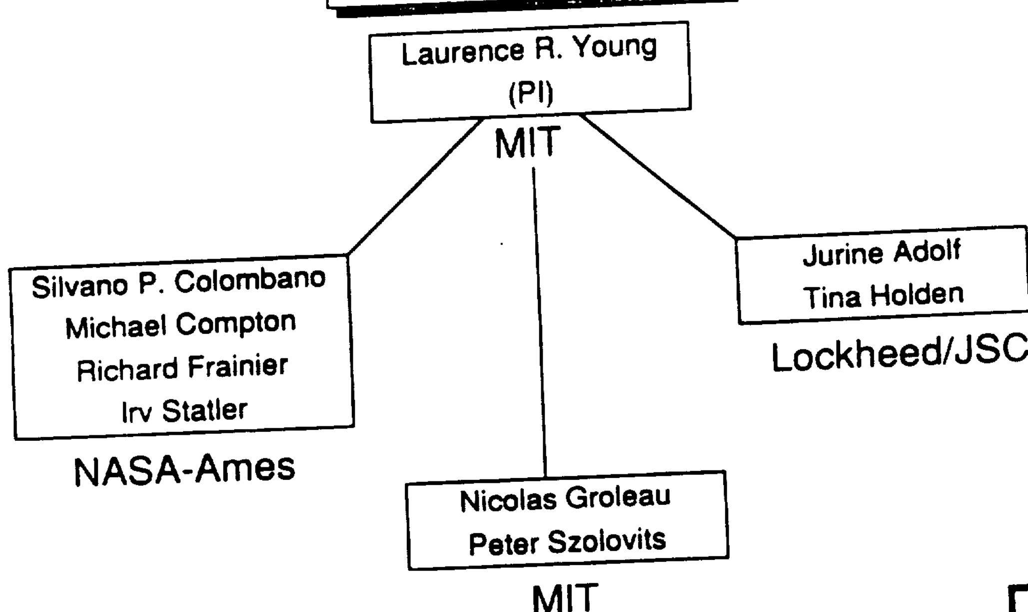
- Totally automatic data analysis/model discovery
- Integrates symbolic AI methods with statistical (numerical) approaches

"PI-in-a-box" as an Astronaut Science Advisor

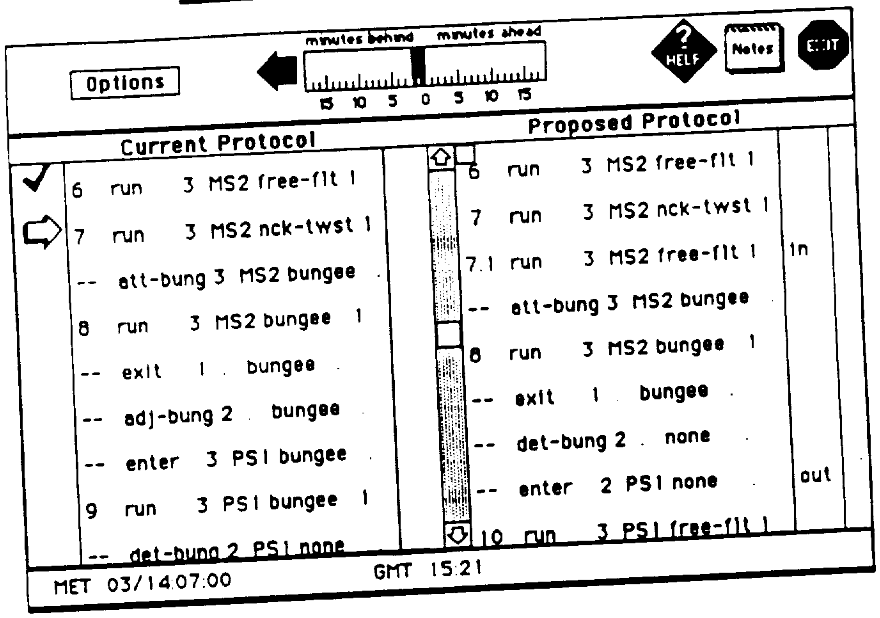
GOALS:

- 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

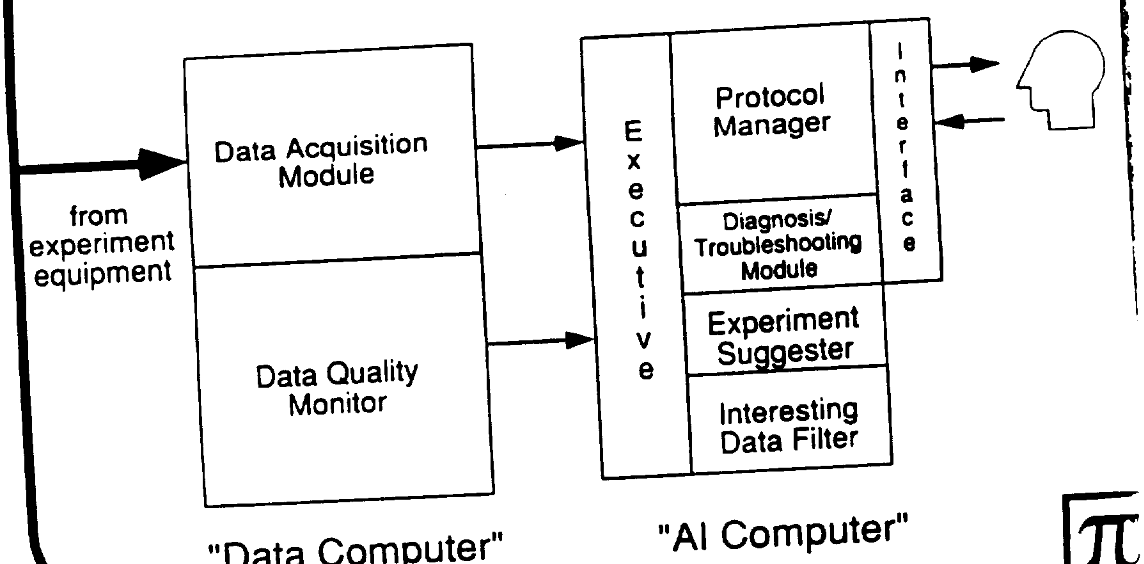
Project Team



Protocol Manager Screen: New Proposed Protocol



System Architecture



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

π

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

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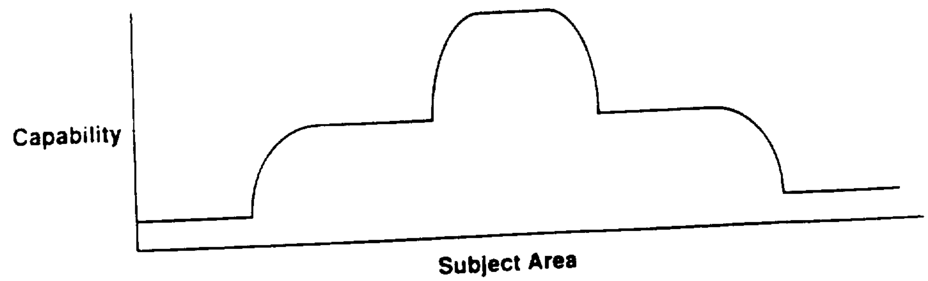
Capabilities of a Human Expert



- 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
CHARLES R. WEISBIN
JET PROPULSION LABORATORY
PASADENA, CALIFORNIA

e-mail address: weisbin@telerobotics.jpl.nasa.gov
office phone number: 818-354-2013 FTS 792-2013

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 CABLING
- 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

	ADVANCED TELEOPERATION	SUPERVISED CONTROL
FOCUS	• NON-REPETITIVE, LESS WELL-MODELED TASKS • COMPUTER-ASSISTED OPERATOR CONTROL (E.G., HUMAN TASK PLANNING WITH REAL-TIME GRAPHIC DISPLAY)	• REPETITIVE, BETTER MODELED TASKS • PROCESS-LEVEL AUTONOMY (E.G., GRASP FIXTURE)
EXAMPLES	• DEPLOYMENT OF LARGE SATELLITES • CUSTOM CUTTING/WELDING REPAIR OPERATIONS	• MULTIPLE BOLT INSERTION/ REMOVAL • POLISHING HIGH-PRECISION SURFACES

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

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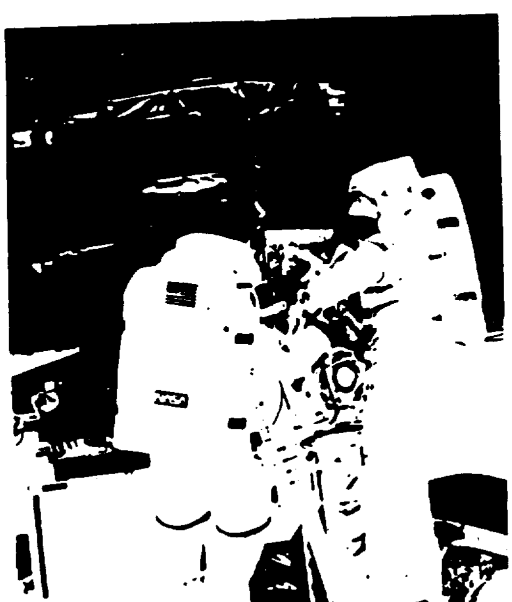
ADVANCED TELEOPERATION

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

AKB. 2-20 90

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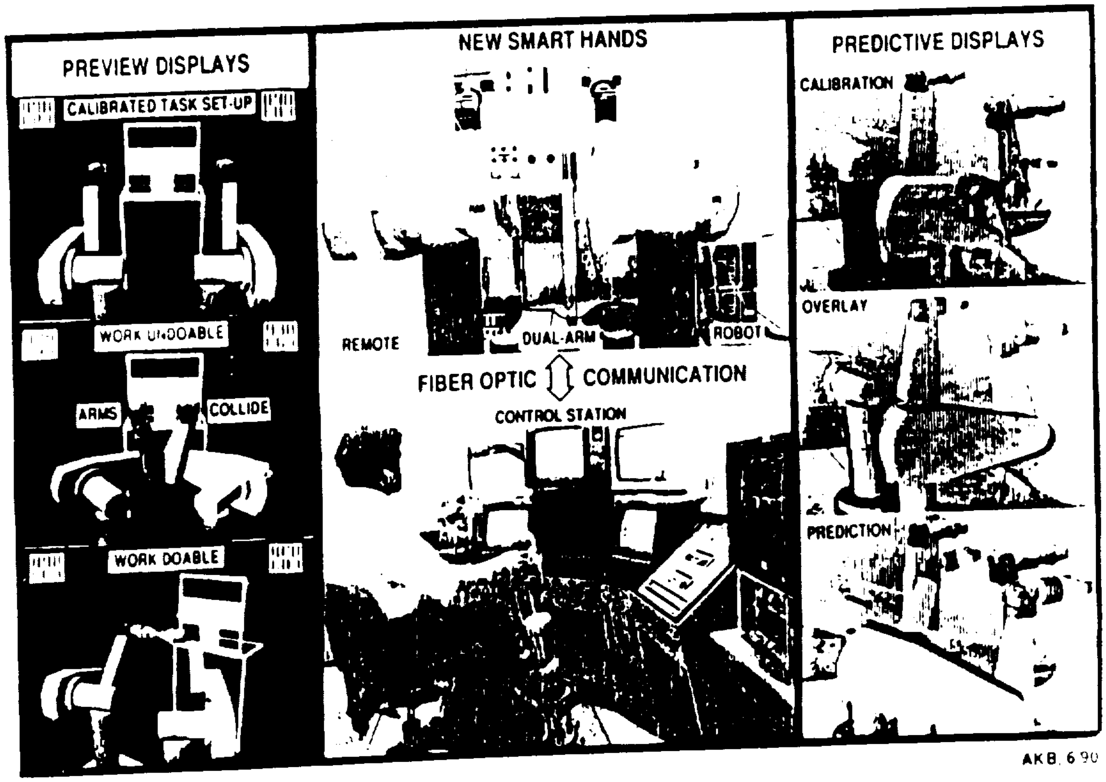
ADVANCED TELEOPERATION: 1990 HIGHLIGHTS SUMMARY



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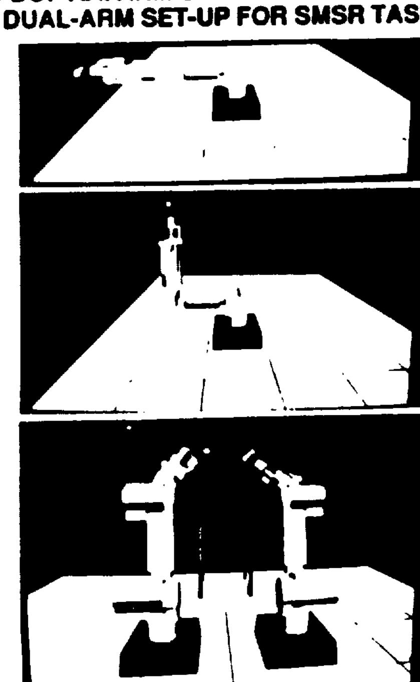
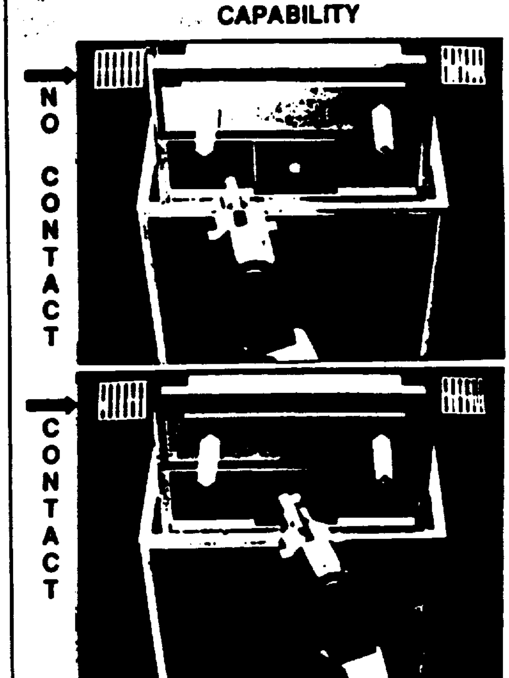
PREVIEW AND FORCE-REFLECTING GRAPHICS DISPLAYS

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



FORCE INDICATING/REFLECTING CAPABILITY



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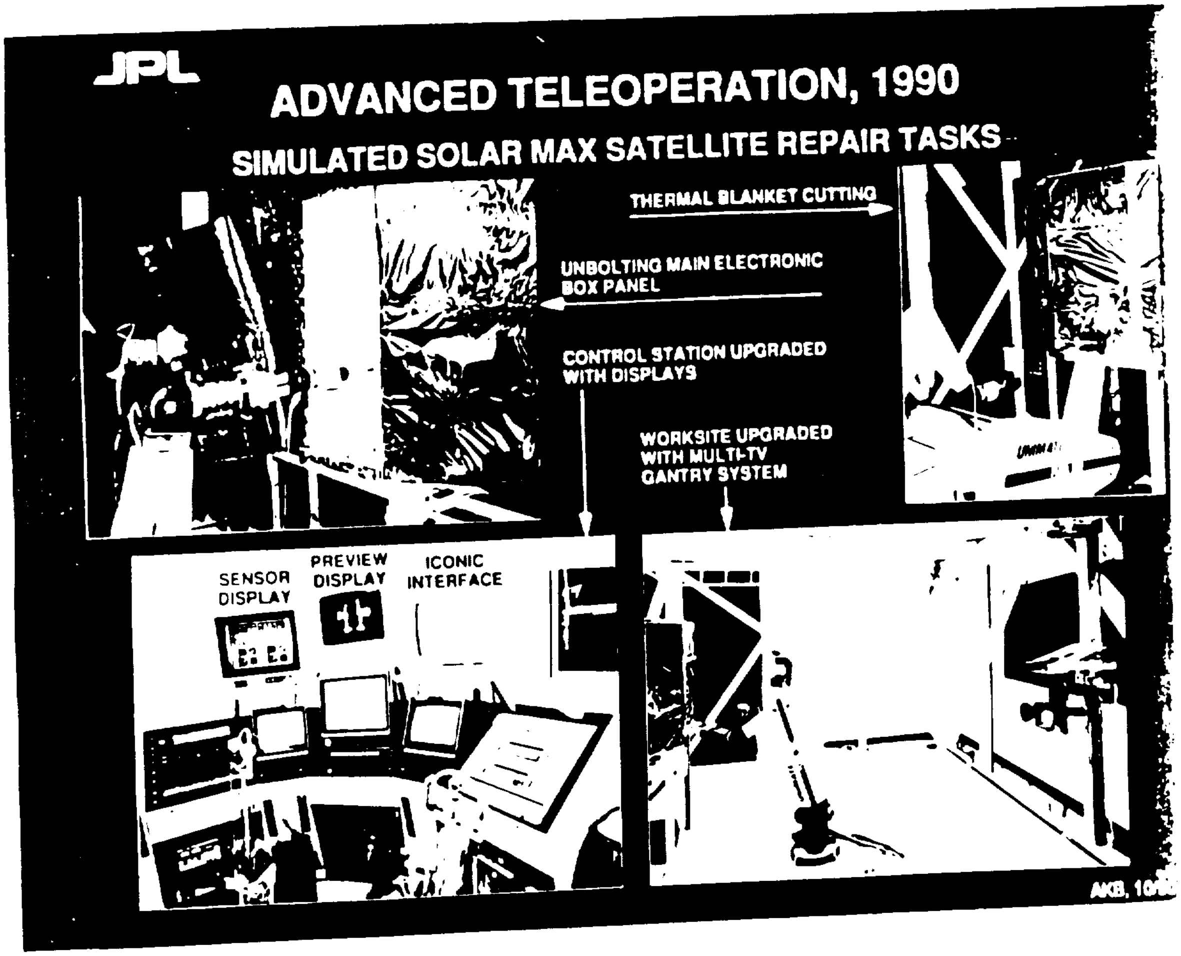

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SOLAR MAX SATELLITE REPAIR EXPERIMENTS

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

USE OF POWER SCREW DRIVER TO REMOVE CONNECTOR SCREWS

AKB

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

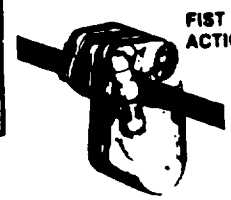
PURE POSITION CONTROL BETTER THAN PURE RATE CONTROL

OBSERVATION:

COMPLIANCE BETTER THAN FORCE REFLECTION

SUBJECTS PREFERRED POSITION CONTROL OVER RATE CONTROL

FORCE-REFLECTING EXOSKELETON ANTHROPOMORPHIC TELEMANIPULATION

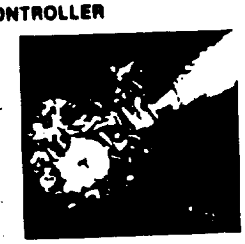


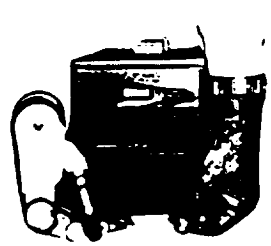
FIST ACTION

MASTER ARM AND CONTROL ELECTRONICS

SLAVE HAND

GLOVE CONTROLLER



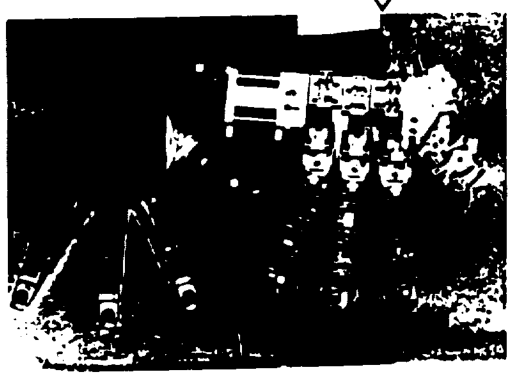


SLAVE AND HUMAN HANDS

DEXTEROUS FINGER ACTIONS

AKB, 6/90

EXOSKELETON
MASTER "GLOVE
HAND" AND
SLAVE HAND



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

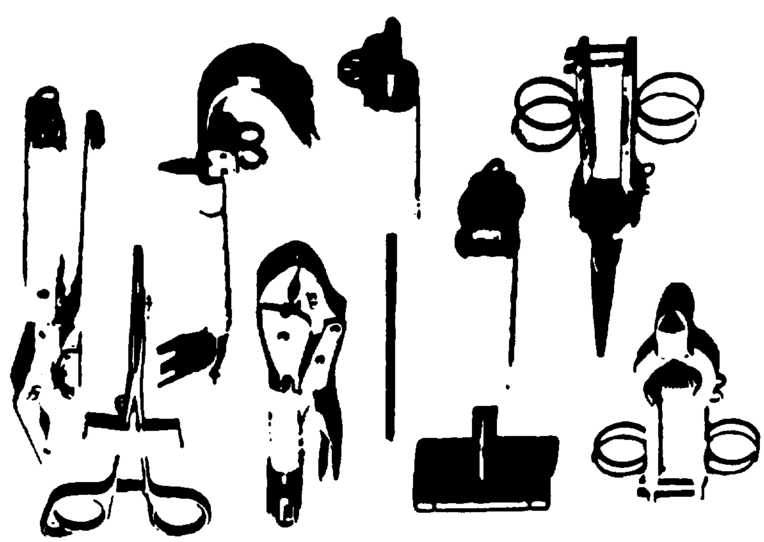
[INFORMATION SOURCE FOR EVA TOOLS/TASKS TEST CANDIDATES: NASA DOCUMENT "EVA CATALOG, TOOLS AND EQUIPMENT", JSC-20466, NOV. 1985.]

AKB, 2 28 91

JPL

CANDIDATES FOR EXOSKELETON TOOL HANDLING TASKS

"EVA" JAM REMOVAL TOOLS



(FROM: NASA DOCUMENT "STS, EVA DESCRIPTION AND DESIGN CRITERIA", JSC-10615, MAY 1983, p. 19)

AKB, 2 28 91 (18)

JUSTIFICATION

- Several studies have indicated that inspection will be an important activity for Space Station Freedom
  - NASA/JSC Final Report, Space Station Freedom External Maintenance Task Team, W. F. Fisher and C. R. Price., July 1990
  - SAIC Blue Panel Report, June 12, 1990
  - NASA Headquarters Report: Office of Space Station, Space Station Freedom Automation and Robotics: An Assessment of the Potential for Increased Productivity, Dec 89
- Use of telerobotics 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

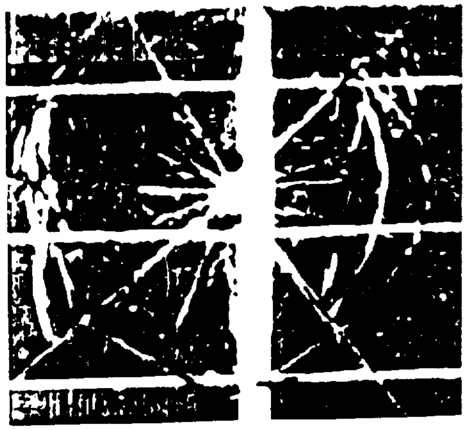
IDENTIFIED INSPECTION TASKS:

- 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 hydrazine concentration
- [illegible] ground process for certifying payloads

REMOTE SURFACE INSPECTION

LONG DURATION EXPOSURE FACILITY (LDEF) EXAMPLES:

(a) 2 cm



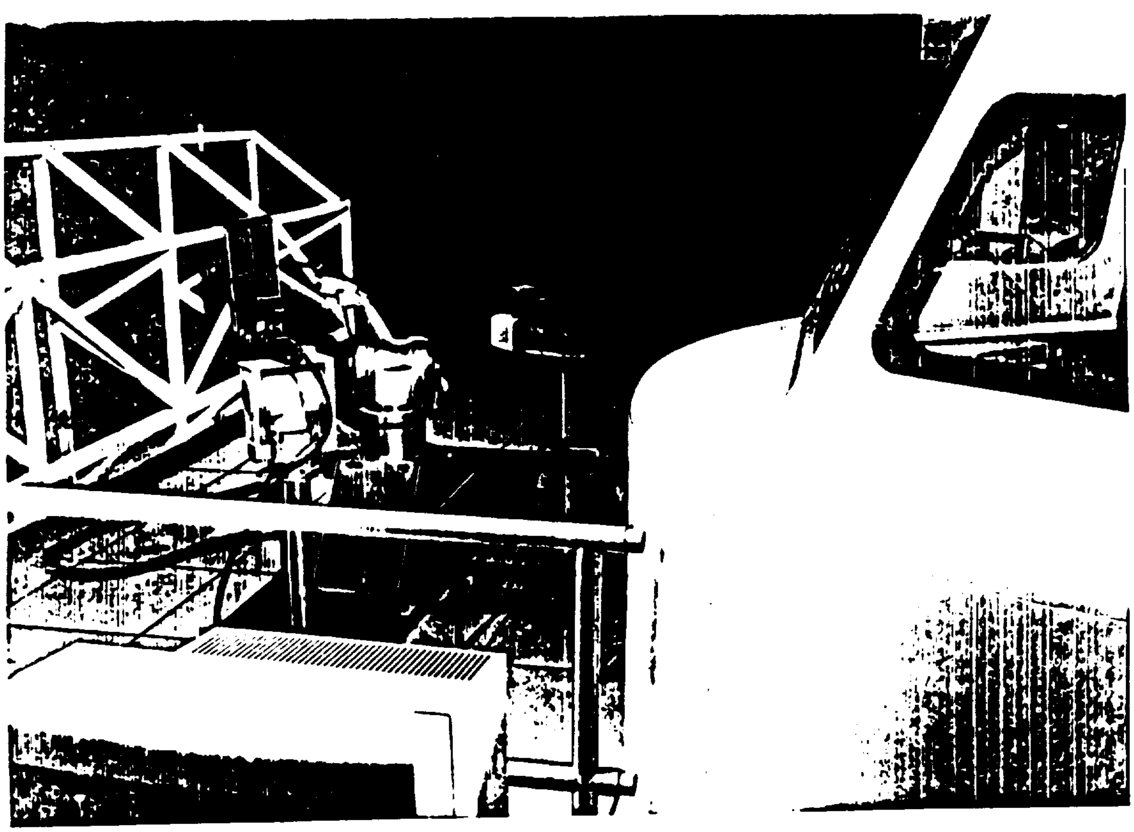
(b) 6cm

(a) Solar array-materials LDEF experiment

(b) Thermal blanket damaged by micometeoroid and delamination

(c) Concentrically-ringed impact feature into the white painted aluminum surface

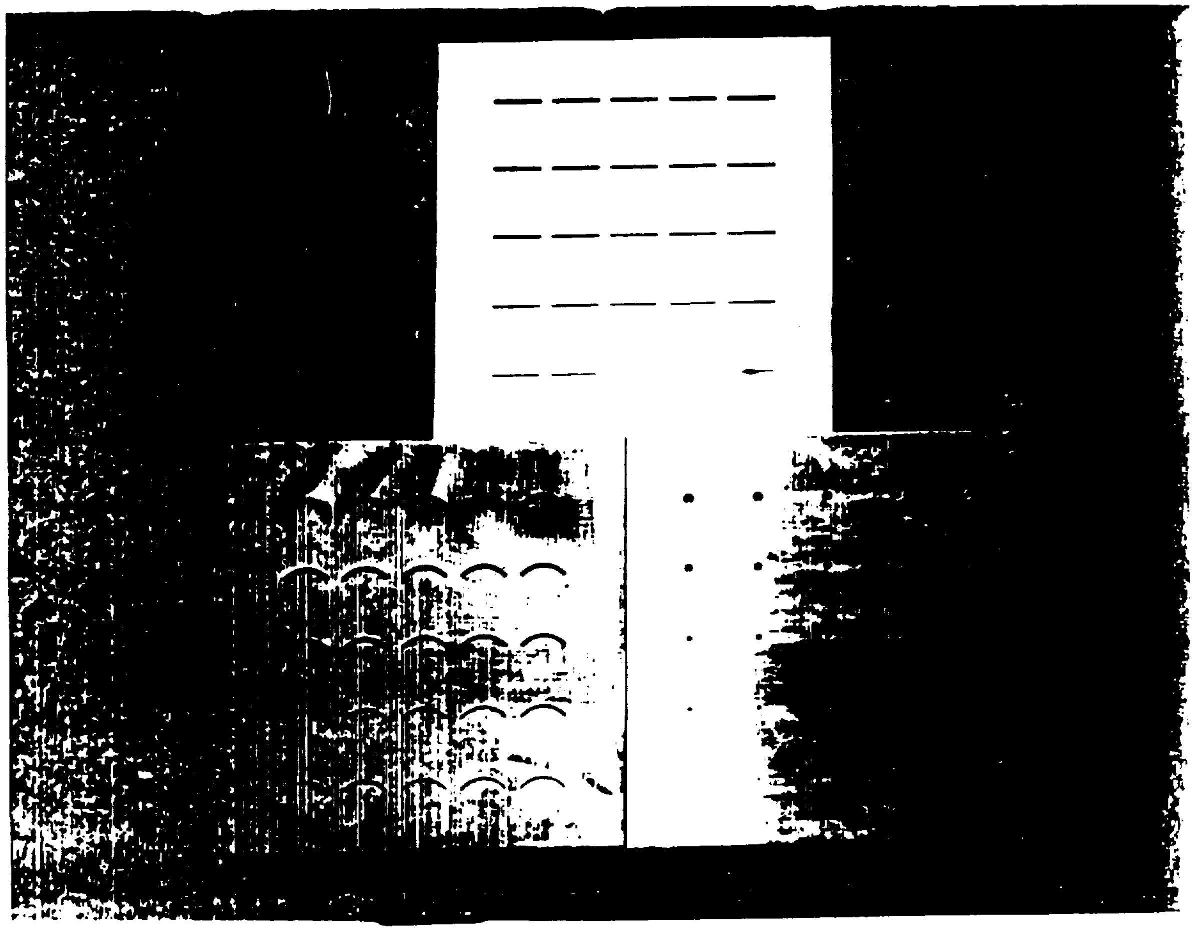
(c) 2cm



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 by using controlled 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 end-point 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

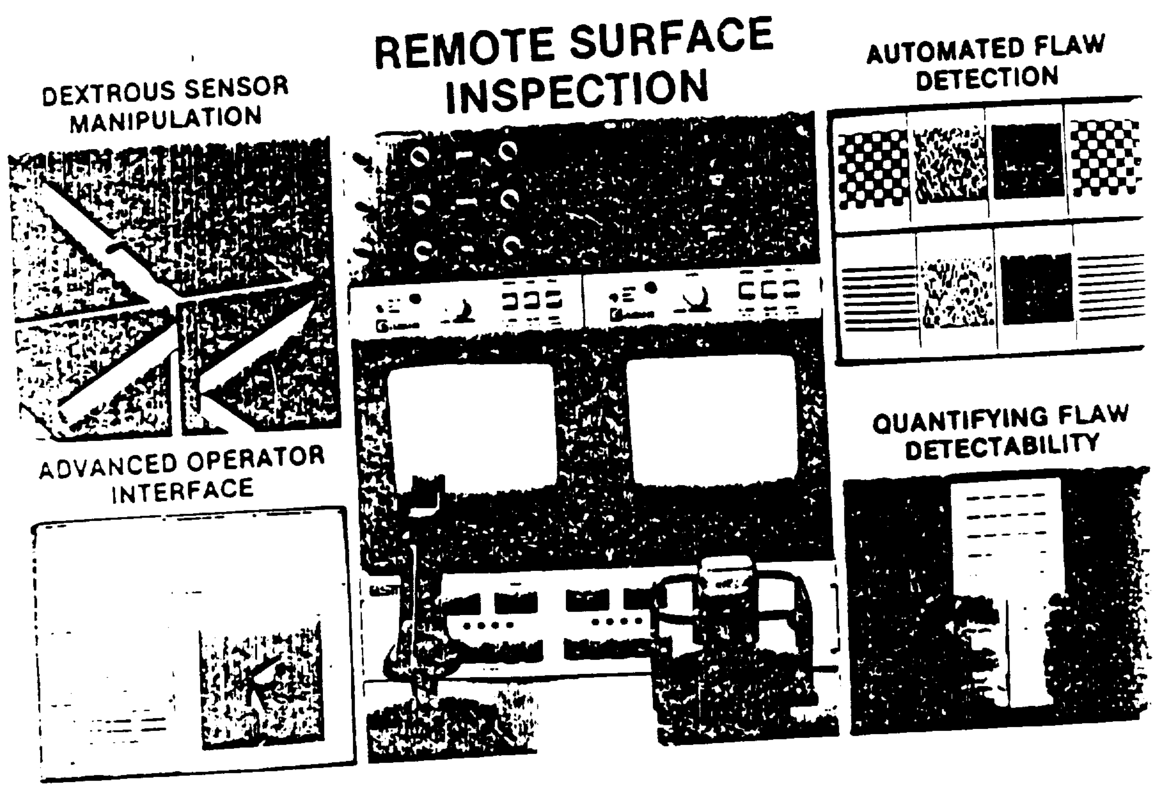
GENERAL APPROACH: Detection of changes between "before" and "after" images of a scene

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 (Threated 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
- Sulfuric 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 cleat exterior door (Thumb Latch Type, Door Closer).
- Retrieve, manipulate, and stow various components (sensor probes, door key, door stops)
- Open Store 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.

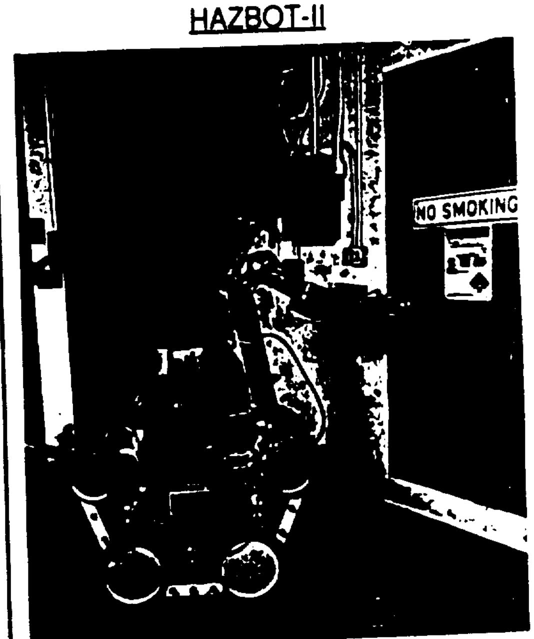
EMERGENCY RESPONSE 9 HWS 11/9/90

JPL EMERGENCY RESPONSE ROBOTICS

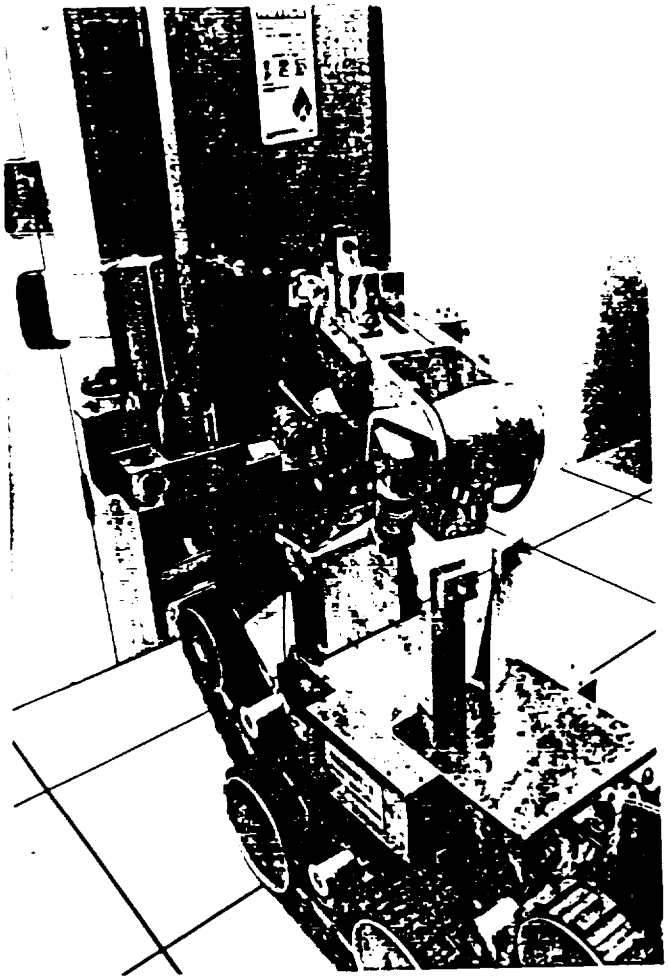
ACCESSING HYPOTHESIZED INCIDENT SITE

HUMAN ENTRY TEAM

HAZBOT-II



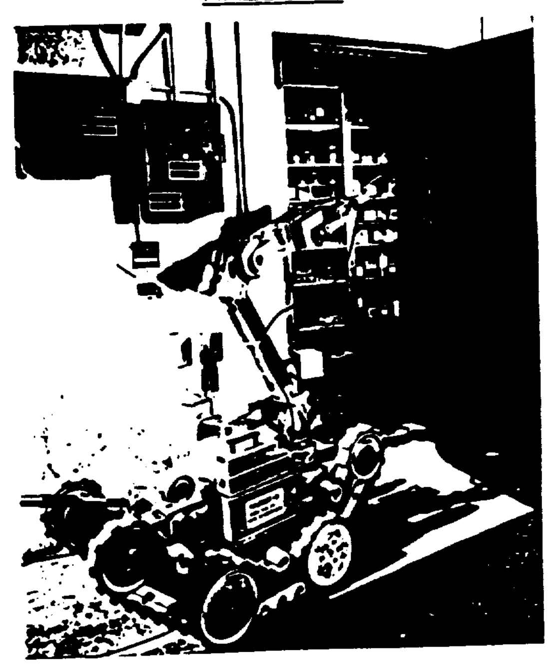
HWS, 2/8/91 (15)



VISUAL AND CHEMICAL SENSOR INSPECTION PRIOR TO PHYSICAL ENTRY

HUMAN ENTRY TEAM

HAZBOT-II



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 stowage and retrieval.
- Existing systems do not support and/or are unable to deploy chemical sensors commonly used in responding to Hazardous Materials incidents.

HWS 6/17/91

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)

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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

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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

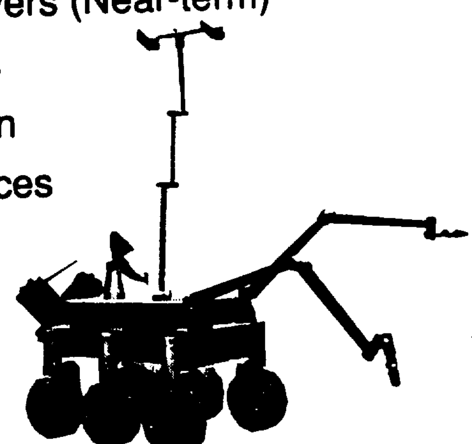
June 26, 1991

SSTAC/ARTS External Review

Planetary Rover Program

Technology Challenges

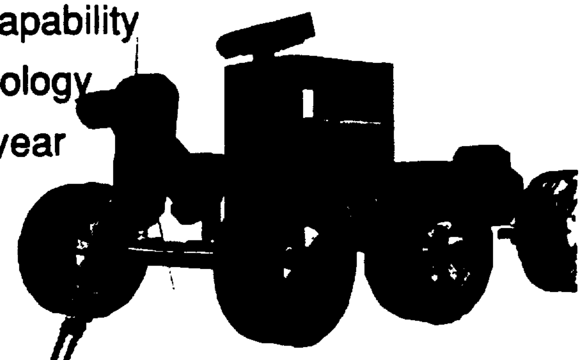
- Missions: Mars Sample Return, Lunar Exploration, Mars Exploration
- Needs: Unmanned Science Rovers (Near-term)
  - Low (2-500Kg) vehicle mass
  - Semi-autonomous navigation
  - 100m-40Km traverse distances
  - SAAP payload compatibility
  - 1-year lifetime (minimum)
  - System autonomy
  - High mobility



Planetary Rover Program

Technology Challenges (con't)

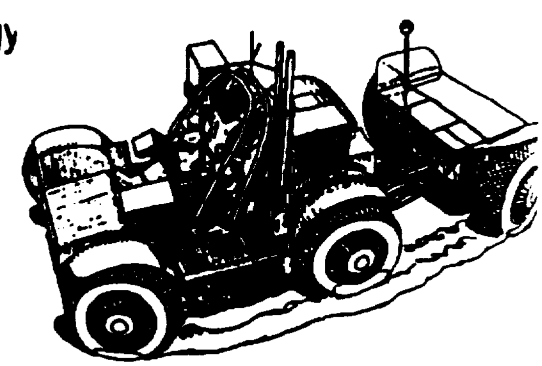
- Misisons: Lunar Outpost Placement, Remote Lunar Science, Lunar VLFA Construction
- Needs: Unmanned Lunar Rovers (Mid-term)
  - 5-year+ operational lifetime
  - Regolith manipulation capability
  - Advanced materials/tribology
  - 1000Km+ traverse per year
  - System Autonomy
  - Long-life mobility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



Planetary Rover Program

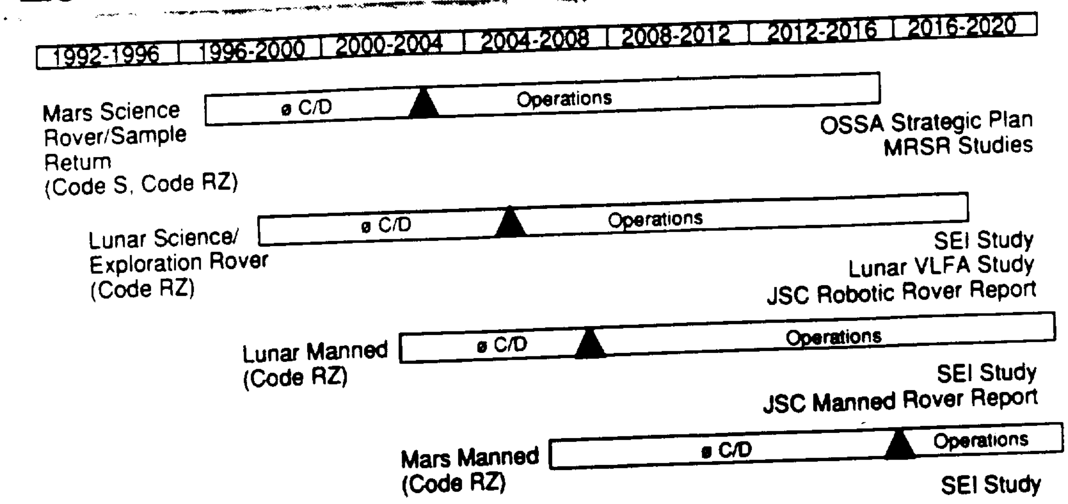
Technology Challenges (con't)

- 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



(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

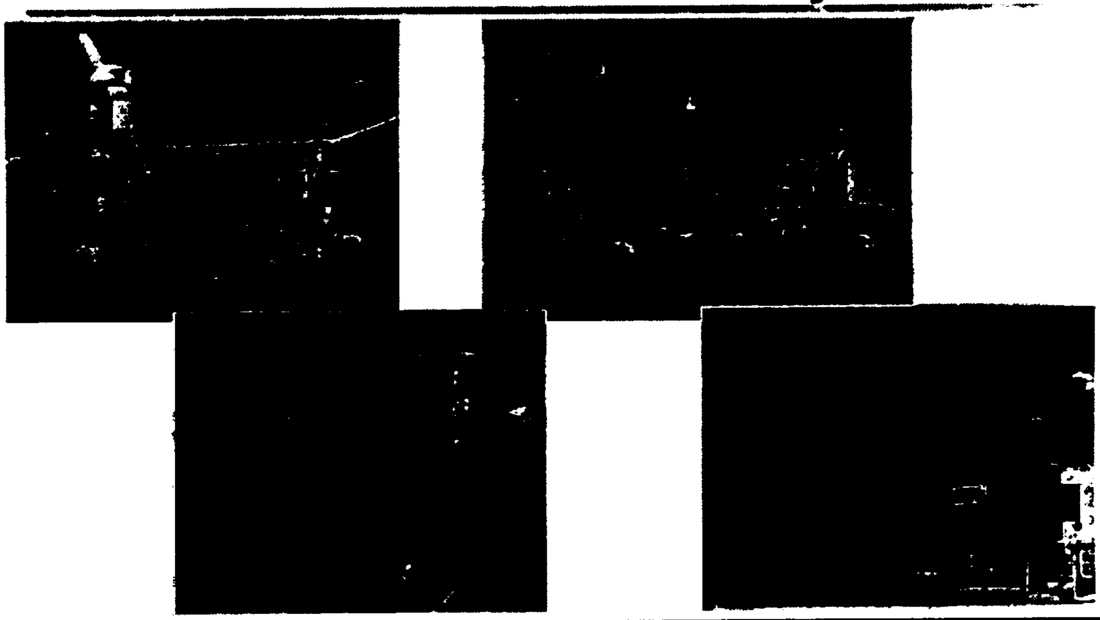
Current State Of The Art - Systems

- 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

Current State Of The Art - Systems



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

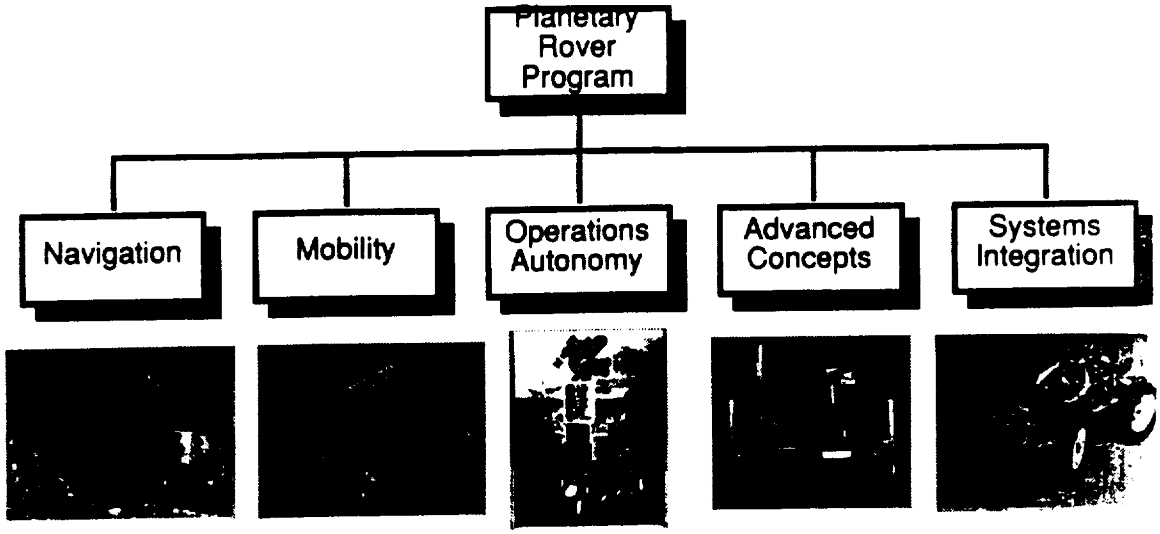
Planetary Rover Program

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 th impact of the new technology on overall system performanc

Planetary Rover Program

Program Structure



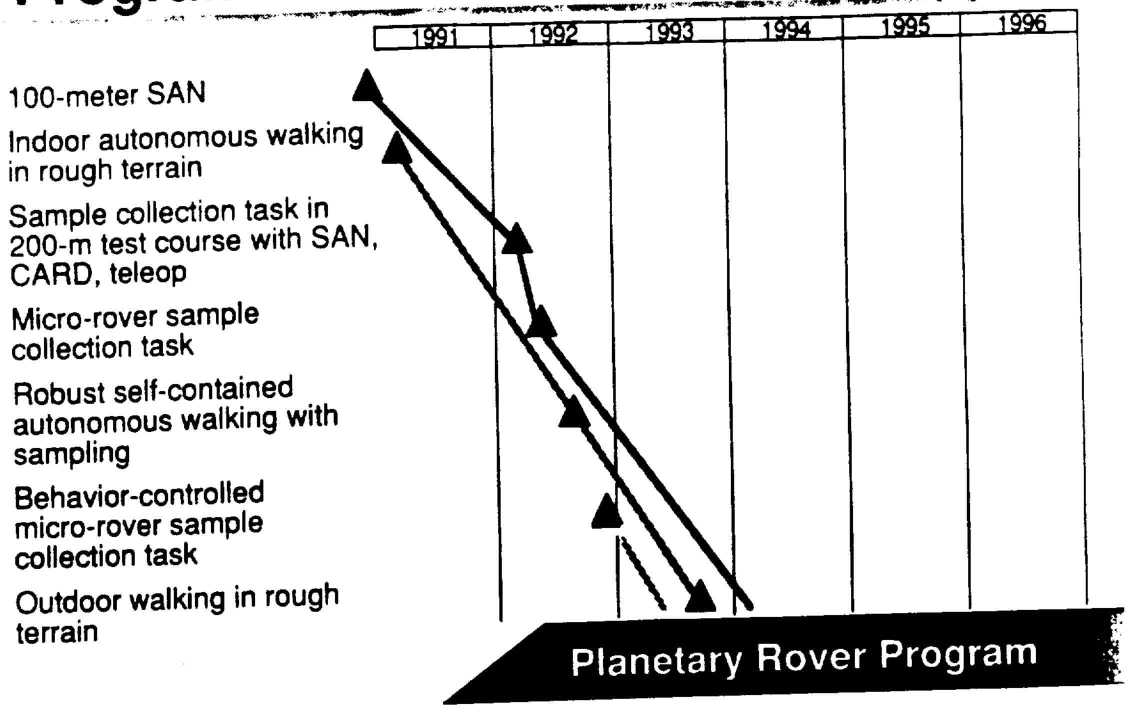
Planetary Rover Program

Program Developments to Date

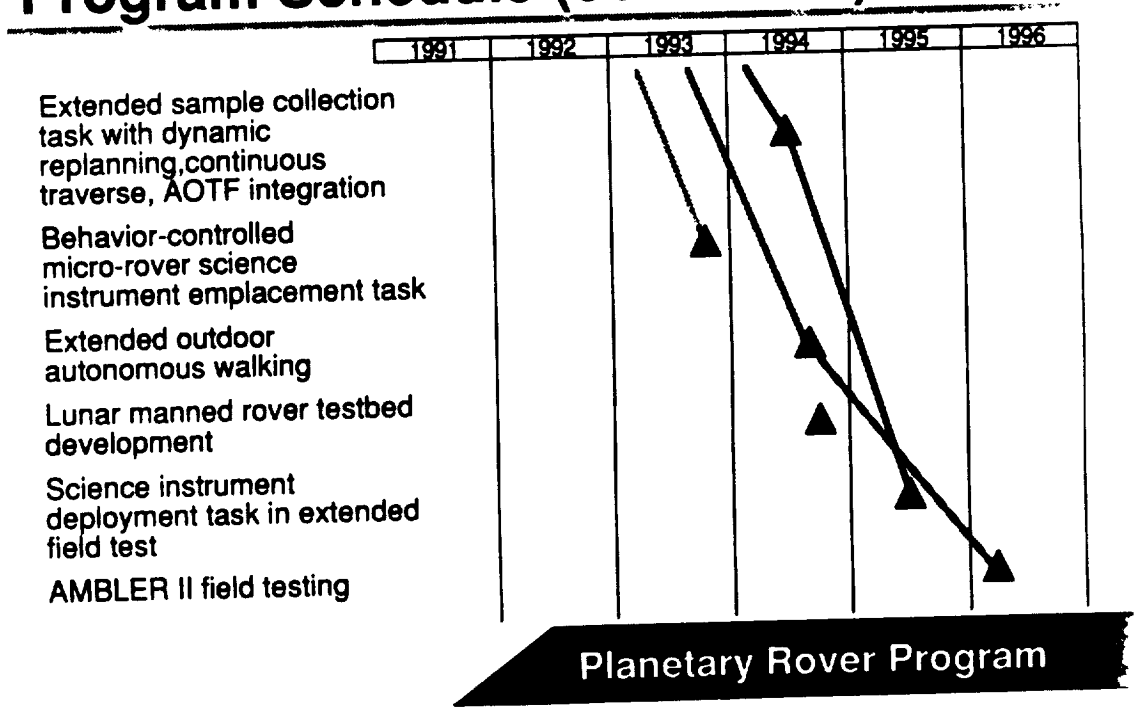
- **Initial SAN**
- **Autonomous walking**
- **Task Control Architecture**
- **Active sensing perception system**
- Local terrain mapper
- Generalized gait planner
- Structured light sample acquisition
- Composite terrain mapping
- Active leveling system
- Legged mobility mechanism design
- Fine powder 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

Planetary Rover Program

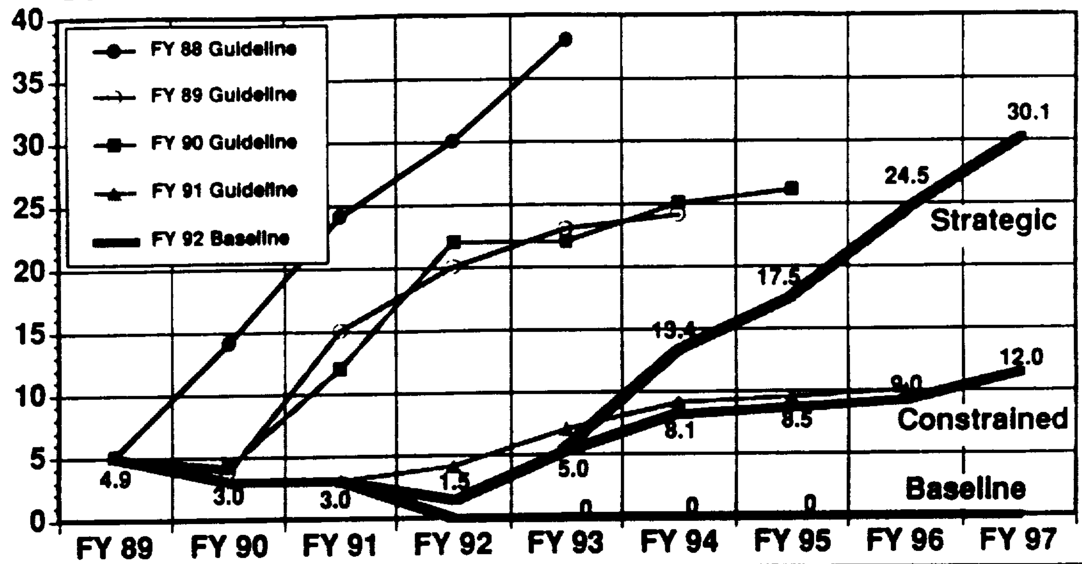
Program Schedule



Program Schedule (continued)



Rover Funding Profile



Planetary Rover Program

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

NASA
OAET

NASA PLANETARY ROVER PROGRAM

ROGER BEDARD
JET PROPULSION LABORATORY

& DAVID LAVERY
NASA HQ/CODE RC

JUNE 26, 1991
SSTAC MEETING

JPL

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

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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

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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

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SCIENCE ROVER

INTRODUCTION

- 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

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VISION

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

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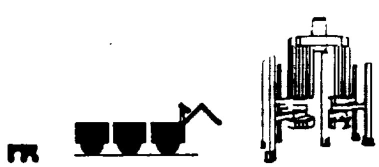
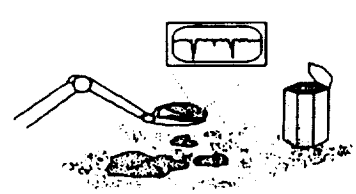
THE APPROACH

INVESTIGATE ROVER TECHNOLOGY OPTIONS



- Different Configurations
- Different Components
- Various Sizes

AND VALIDATE SYSTEM TASK CAPABILITY



- Scientific Exploration
- Surface & Subsurfac Sample Acquisition, Analysis and Preservation
- Science Instrument Emplacement

IN RELEVANT EARTH TEST ENVIRONMENTS

- JPL Arroyo, Edwards or Death Valley

- At Various Levels of Human Control
- With Various Levels of Time Delay (from 0 to 40 minutes)

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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

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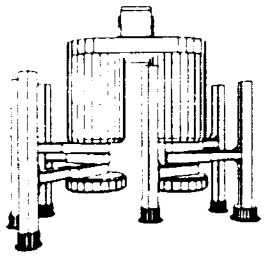
NASA OAET	CMU LEGGED VEHICLE MOBILITY AND NAVIGATION	ROVER

CMU 'AMBLER'



OBJECTIVES

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

DEVELOP AUTONOMOUS NAVIGATION FOR AMBLER

PARTICIPANTS AND FACILITIES

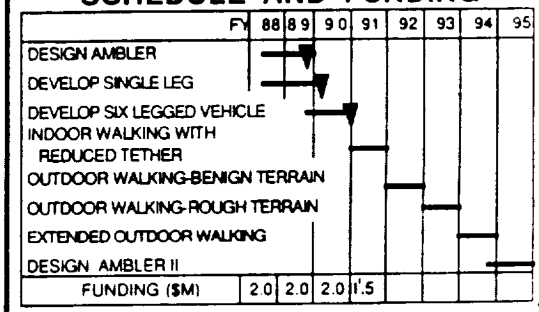
PARTICIPANTS

- CARNEGIE MELLON UNIVERSITY

FACILITIES

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

SCHEDULE AND FUNDING



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NASA OAET	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

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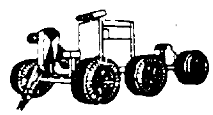
NASA OAET	JPL WHEELED VEHICLE MOBILITY AND NAVIGATION

ROBBY

OUTDOOR ROVER (1000 KG)



TOOTH - INDOOR MICROROVER (1 KG)

ROCKY 3 - OUTDOOR MINIROVER (20 KG)

ROCKY 4 - OUTDOOR MICROROVER (2.5 KG)

OBJECTIVE

Develop remotely piloted science rovers, covering a size ranging from 1 to 1000 kg, that can

- o Perform scientific exploration
- o Identify, acquire, analyze and preserve science samples
- o 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

	89	90	91	92	93	94	95
DEVELOP ROBBY	▼						
100 METER ROBBY AUTO TRAVERSE		▼					
ROCKY SAMPLE ACQUIISTION			▽				
ROBBY SAMPLE ACQUISITION				▽			
MICROROVER SAMPLE ACQUISITION				▽			
DEPLOY SCIENCE INSTRUMENTS					▽		
CONTINUOUS TRAVERSE AND EXTENDED TESTING							▽
JPL FUNDING ($M)	1.5	1.2	1.0				

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OAET	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 DEMO-STRATING SIMPLE BUT ROBUST MICRO-ROVER BEHAVIOR

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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

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PILOTED ROVER TECH ASSESSMENT STUDY

ROVER

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

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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

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SUMMARY 2 OF 2

- 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 OR LACK OF FY 92 FUNDING

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omiT

Sensors

INFORMATION SCIENCE & HUMAN FACTORS DIVISION

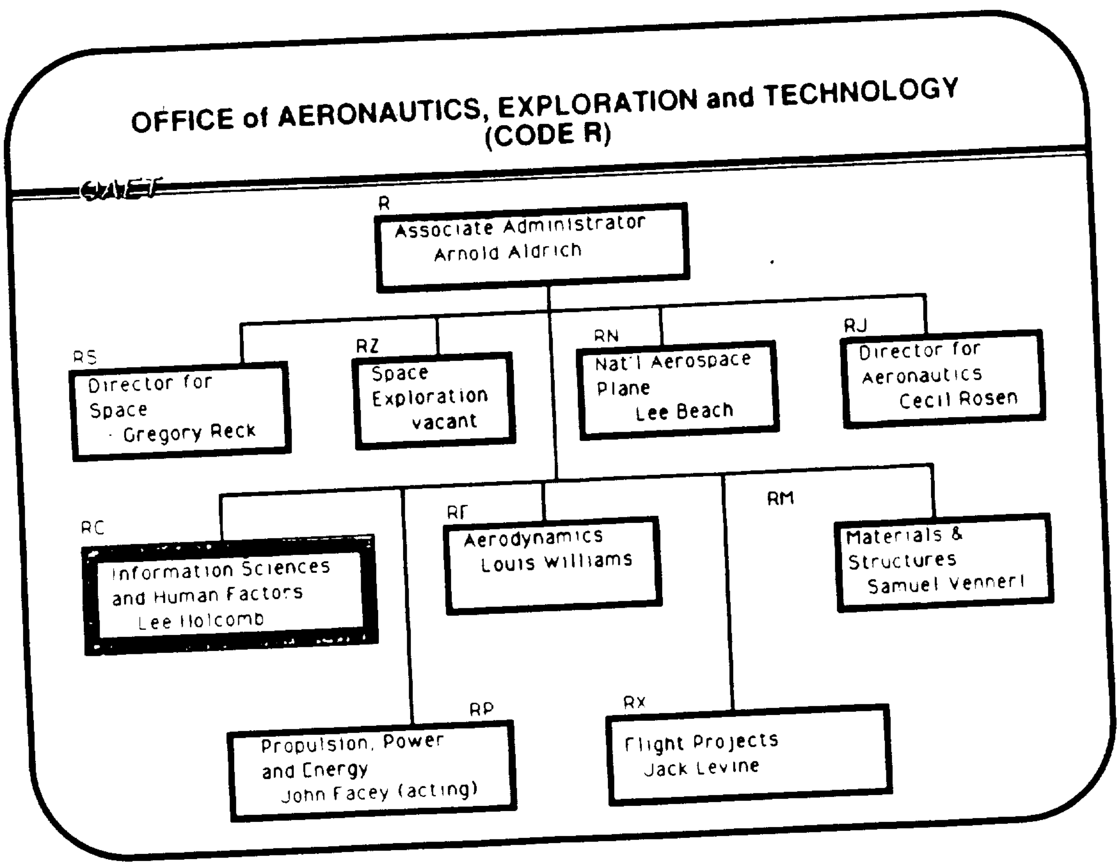
OAET

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**



SCIENCE SENSING TECHNOLOGY PROGRAM

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- "DURING THE 1990's", ARRAYS OF INFRARED DETECTORS, THE ABILITY TO BUILD LARGE OPTICAL TELESCOPES, IMPROVED ANGULAR RESOLUTION AT A VARIETY OF WAVELENGTHS, NEW ELECTRONIC DETECTORS, "...... WILL MAKE POSSIBLE AN IMPROVED VIEW OF THE UNIVERSE."

  --- ASTRONOMY & ASTROPHYSICS 1991 NATIONAL RESEARCH COUNCIL, CHAIR JOHN BAHCALL.

- "ADVANCE SENSOR TECHNOLOGY IS ESSENTIAL TO LEADERSHIP IN SPACE SCIENCE AND APPLICATIONS. THE COMMITTEE RECOMMENDS EMPHASIS ON FOUR PRINCIPLE .... AREAS:
  - LARGE APERTURE OPTICAL & QUASI - OPTICAL SYSTEMS.
  - DETECTION DEVICES AND SYSTEMS.
  - CRYOGENIC SYSTEMS, AND
  - IN - SITU ANALYSIS AND SAMPLE RETURN SYSTEMS".

  --- SPACE TECHNOLOGY TO MEET FUTURE NEEDS, AERONAUTICS & SPACE ENGINEERING BOARD, 1987.

6.24.91

SCIENCE SENSING TECHNOLOGY PROGRAM

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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

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OSSA TECHNOLOGY NEEDS

	NEAR TERM NEED	MID-TERM NEED	FAR-TERM NEED
HIGHEST PRIORITY	Sub mm & μ wave Sensing Long Life Cryo Coolers/Cryo Shielding High Energy Detectors Sensor Readout Electronics Vibration Isolation Technology Efficient Quiet Refrigerator Freezer Extreme Upper Atmosphere Instr. Platforms	Long Life, Stable, Tunable Lasers Solar Probe/Mercury Orbiter Thermal Protect High Vol./Density/Rate Onboard Data Storage Interferometer Specific Technology	Structures: Large/Controlled/Deployed Ant a Robotics Precision Inter S/C Ranging/Positioning 50-100 Kilowatt Ion Propulsion (NEP) Large Filled Apertures Parallel S/W Env. for Model&Data Visualization Computational Techniques
2ND HIGHEST PRIORITY	High Frame Rate/Res. Video/Data Compress 2.4 to 4 Meter 100 K Lightweight PSR Solar Arrays/Cells Automated Biomedical Analysis Radiation Hardened Parts/Detectors Long Life/High Energy Density Batteries Real Time Environmental Control Space Qualified Masers/Ion Clocks Fluid Diagnostics	Auto Sequencing & CMD Generation Auto S/C Monitoring & Fault Recovery 32 GHz TWT/Optical Communications Telescience/Telepresence/Art. Intelligence Improved EVA Suit/PLSS (EMU) Combustion Devices Plasma Wave Antenna/Thermal	SIS 3 THz Heterodyne Receiver SETI Detector Technologies Mini Ascent Vehicle/Lander Deceleration Radiation Shielding for Crews SAAP Probes/In Situ Instr's/Penetrators Human Artificial Gravity Systems X Ray Optics Technology Returned-Sample Biobarrier Analysis Cap High Resolution Spectrometer
3RD HIGHEST PRIORITY	Descent Imaging/Mini RTG/Mini Camera K Band Transponders Ultra High Gigabit/sec. Telemetry Mini Spacecraft Subsystems Real-Time Radiation Monitoring Solid/Liquid Interface Characterization Laser Light Scattering High-Temperature Mat'ls for Furnaces Field Portable Gas Chromatographs Adv. Furnace Technology	Regenerative Life Support Thermal Control System Non-Contact Temp. Measurement 3-D Packaging for 1MB Solid State Chips Microbial Decontamination Methods Animal and Plant Reproduction Aids Special Purpose Bioreactor Simulator Syst Rapid Subject/Sample Delivery & Return Capability	Autonomous Rendezvous/Sample Xfer/Landing Non Destructive Monitoring Capability Low Drift Gyros/Trackers/Actuators Heat Shield for 16 km/sec Earth entry Partial-G/μ-G Medical Care Systems Dust Protection/Jupiter's Rings Non Destructive Cosmic Dust Collection CELSS Support Technologies

APRIL 20, 1991
JCM 6834

SPACE SCIENCE TECHNOLOGY PROGRAM

Science Sensing	Observatory Systems	In Situ Science	Science Information
DIRECT DETECTORS	TELESCOPE OPTICAL SYSTEMS	PROBES AND PENETRATORS	ARCHIVING AND RETRIEVAL
SUB-MILLIMETER	SENSOR OPTICAL SYSTEMS	SAMPLE ACQUISITION ANALYSIS AND PRESERVATION	DATA VISUALIZATION AND ANALYSIS
LASER SENSING	COOLERS & CRYOGENICS		
ACTIVE MICROWAVE	PRECISION INSTRUMENT POINTING		
PASSIVE MICROWAVE	MICRO-PRECISION CSI		
SENSOR READOUTS			
OPTO-ELECTRONICS			

JUNE 17, 1991

SCIENCE SENSING TECHNOLOGY PROGRAM

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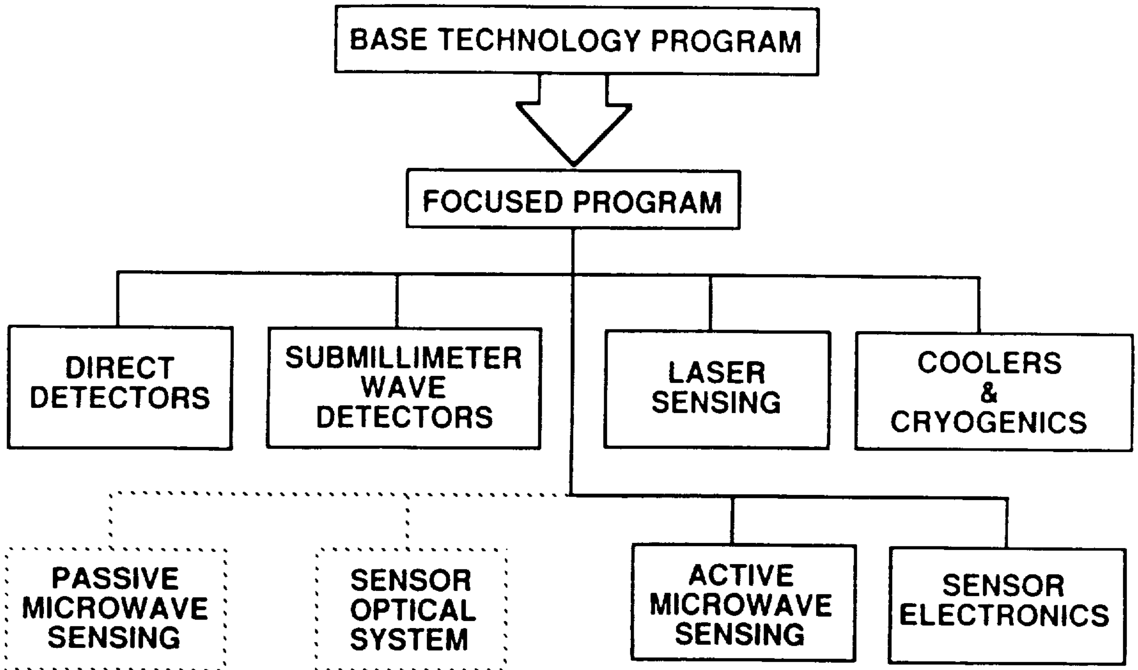

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SCIENCE SENSING TECHNOLOGY PROGRAM

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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.

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SCIENCE SENSING TECHNOLOGY PROGRAM

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SENSOR BASED PROGRAM

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

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SENSOR BASE PROGRAM

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ON - GOING

- 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

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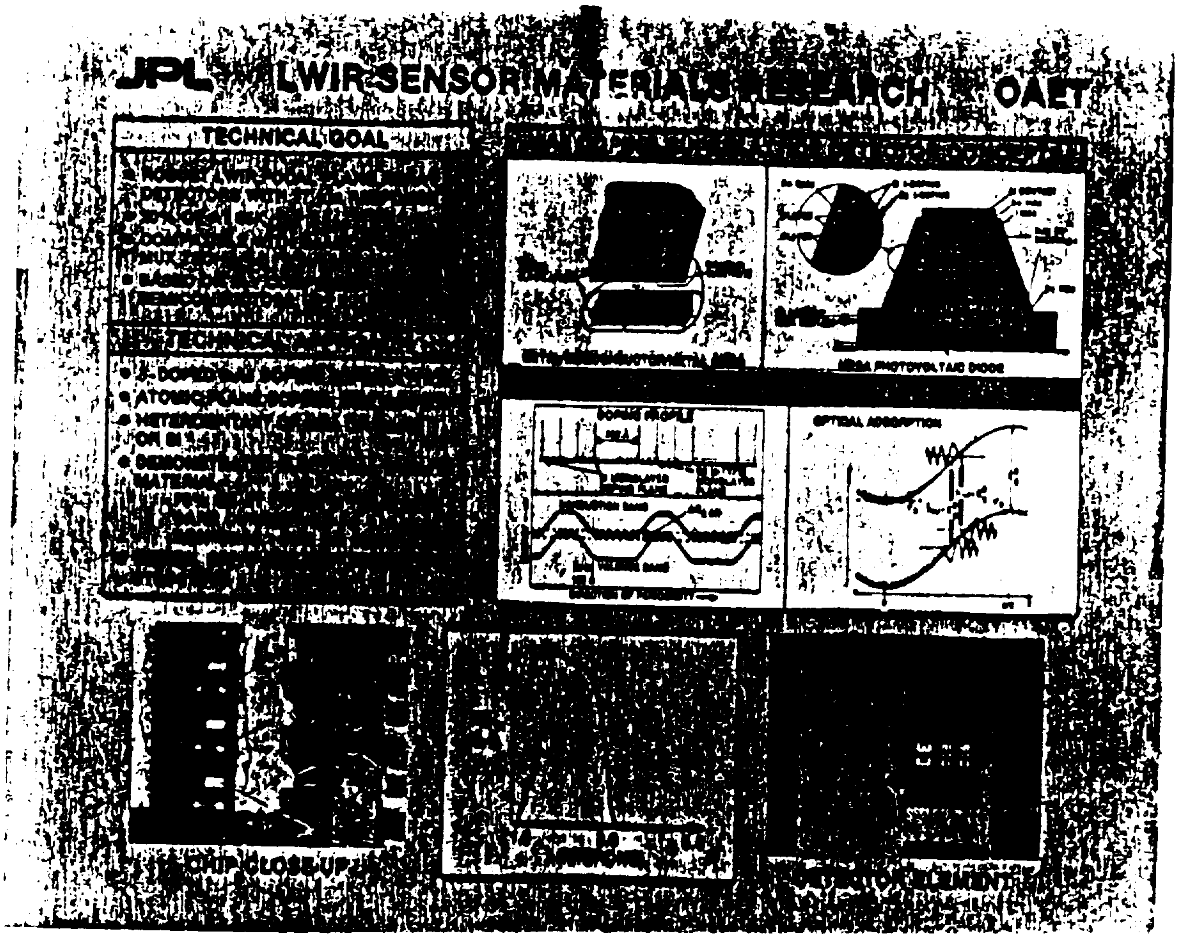
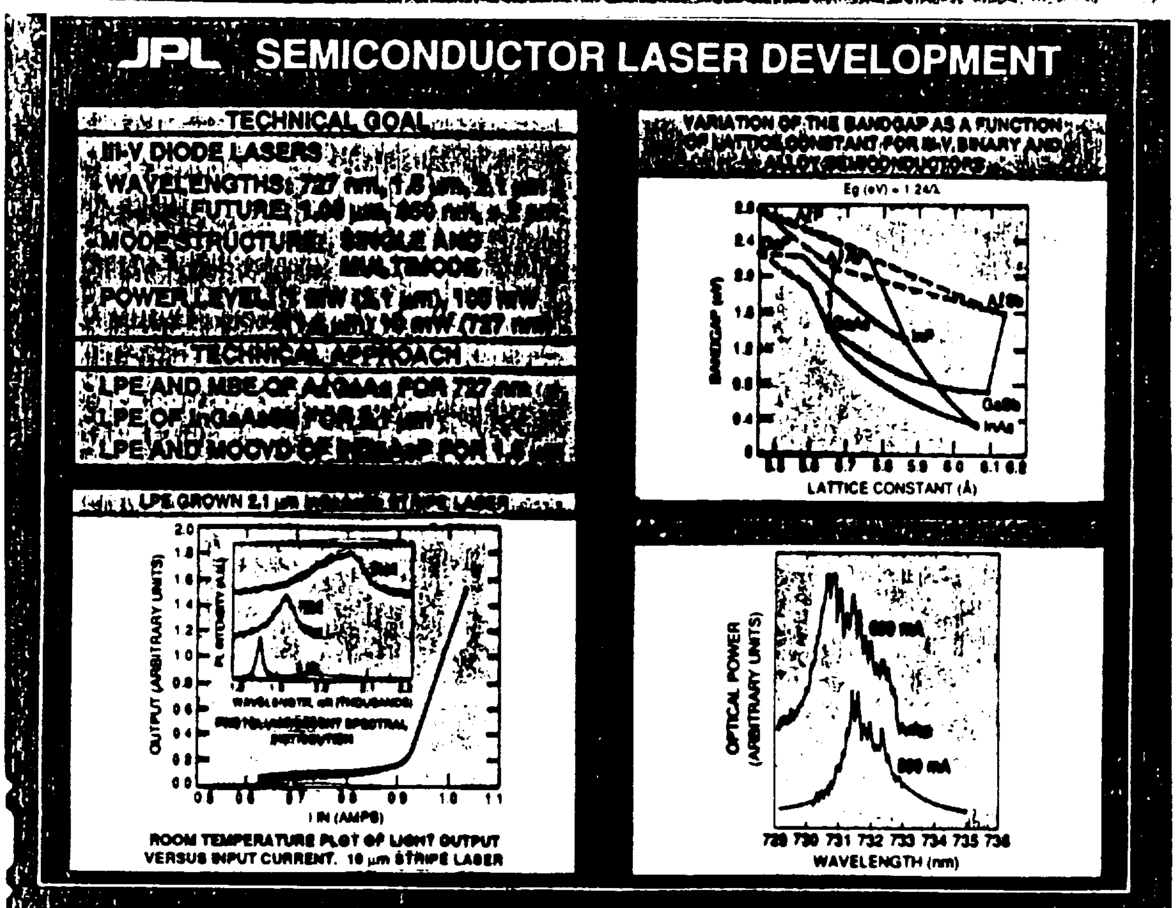
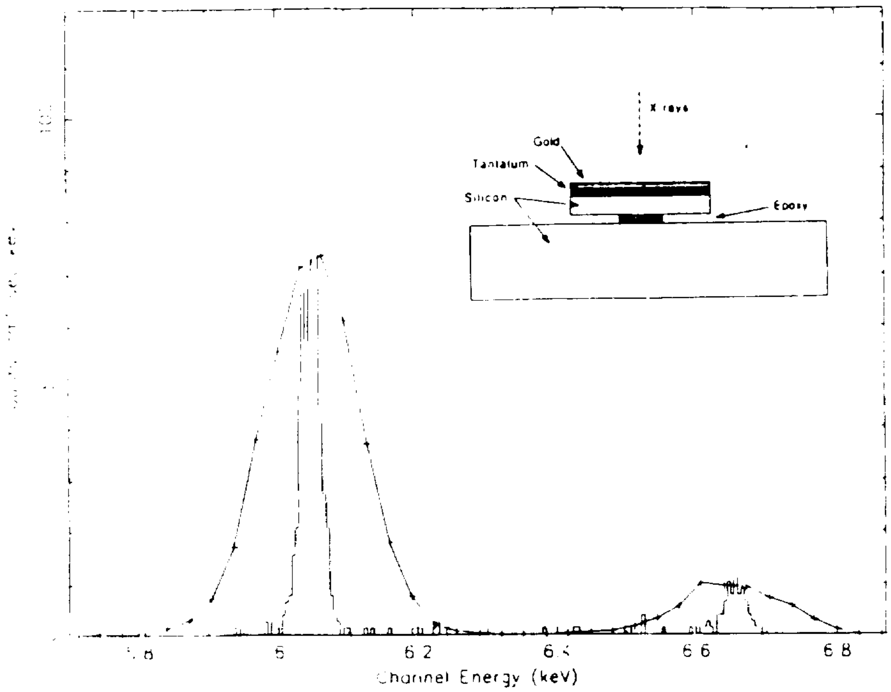

JPL
LWIR SENSOR MATERIALS RESEARCH
TECHNICAL GOAL


JPL SEMICONDUCTOR LASER DEVELOPMENT
TECHNICAL GOAL
III-V DIODE LASERS
TECHNICAL APPROACH
Eg (eV) = 1.24/λ
BANDGAP (eV)
LATTICE CONSTANT (Å)
GaSb
InAs
InP
OUTPUT (ARBITRARY UNITS)
I IN (AMPS)
ROOM TEMPERATURE PLOT OF LIGHT OUTPUT
VERSUS INPUT CURRENT. 10 μm STRIPE LASER
OPTICAL POWER
(ARBITRARY UNITS)
729 730 731 732 733 734 735 736
WAVELENGTH (nm)

X-ray Calorimeters with Superconducting Energy Converters

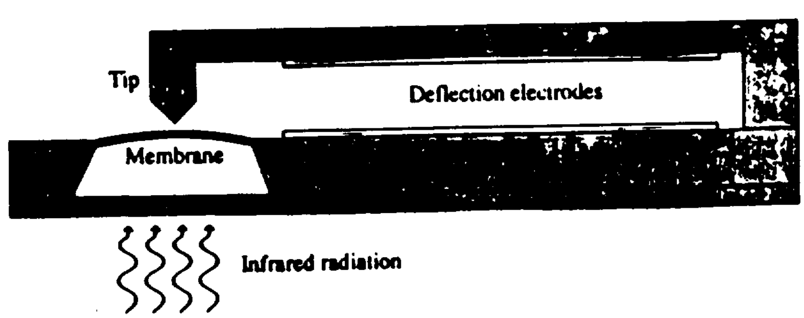


Comparison of Fe-55 spectrum taken with a calorimeter with superconducting Ta absorber(see inset) and a solid state detector (curve with markers). The resolution of the calorimeter is 30 eV FWHM, 5 times better than the solid state detector. Of this 30 eV, 20 eV is due to the superconducting absorber.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

JPL **OAET**

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

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- 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.

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SENSOR BASE PROGRAM

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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

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SCIENCE SENSOR TECHNOLOGY FOCUSED PROGRAM FUNDING

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TECHNOLOGY AREA		FY '92	FY '93	FY '94	FY '95	FY '96	FY '97
SENSOR MATERIALS RESEARCH	BASELINE	300	300	300	300	300	300
	AUGMENTATION	—	160	320	480	480	640
INNOVATIVE SENSOR DEVICE RESEARCH	BASELINE	750	750	750	750	750	750
	AUGMENTATION	—	400	800	1,200	1,200	1,600
SENSOR SUPPORT TECHNOLOGY	BASELINE	450	450	450	450	450	450
	AUGMENTATION	—	240	480	720	720	960
SUB TOTALS	BASELINE	1,500	1,500	1,500	1,500	1,500	1,500
	AUGMENTATION	—	800	1,600	2,400	2,400	3,200
TOTALS	3X (AUGMENT)	1,500	2,300	3,100	3,900	3,900	4,700
	STRATEGIC	1,500	2,500	3,500	4,500	4,500	5,500

6 24 91

SENSOR BASE PROGRAM (AUGMENTED)

OAET

- **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.*

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SENSOR BASE PROGRAM (AUGMENTED)

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- **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.*

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SENSOR BASE PROGRAM (AUGMENTED)

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- **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.*

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SCIENCE SENSING TECHNOLOGY PROGRAM

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STATE OF THE ART	TODAY	GOALS
DIRECT DETECTORS		
GAMMA RAY / X - RAY	HIGH PURITY SI AND Ge DETECTORS HgI DISCRETE DETECTORS SCINTILLATOR - MICROCHANNEL PLATES	POSITION SENSITIVITY (1000 X 1000 ARRAYS LOW - NOISE PREAMPLIFIERS
UV / VISIBLE	SI CCD's, MICROCHANNEL PLATES	CUSTOM DESIGN CAPABILITY HIGHER QUANTUM EFFICIENCY ENHANCED WAVE LENGTH RANGE
SWIR, MWIR (1 - 5μm)	PV Hg CdTe,InSb SCHOTTKY PtSI	LARGER ARRAY, IMPROVED D HIGHER QE, LOW - NOISE READOUTS
LWIR, ULWIR (5 - 30μm)	PV OR PC Hg Cd Te 12μm SI=x IBC (<12K)	LARGER PV ARRAYS t >65k t = 30k LARGER ARRAYS, LOW - NOISE READOUTS
FIR (30 - 1– μm)	STRESSED AND UNSTRESSED GE=X SI OR Ge BOLOMETERS (<1K)	ARRAY CAPABILITY (SAME >4000 X 4000) LOW - NOISE READOUTS VERY LOW NEP (BELOW 10^{-18} W / $\sqrt{Hz}$
BREADBOARD (1 - 1000μm)	PYROELECTRICS, THERMOPILES	HIGHER D * (>100K) LARGER ARRAYS (UP TO 1000 X 1000) LARGER △ !

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SCIENCE SENSING DIRECT DETECTORS

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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 (SOME ≥~ 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

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MILESTONES - DIRECT DETECTORS

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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*

6.24.91

ARC

Low-Background IR Detector Technology

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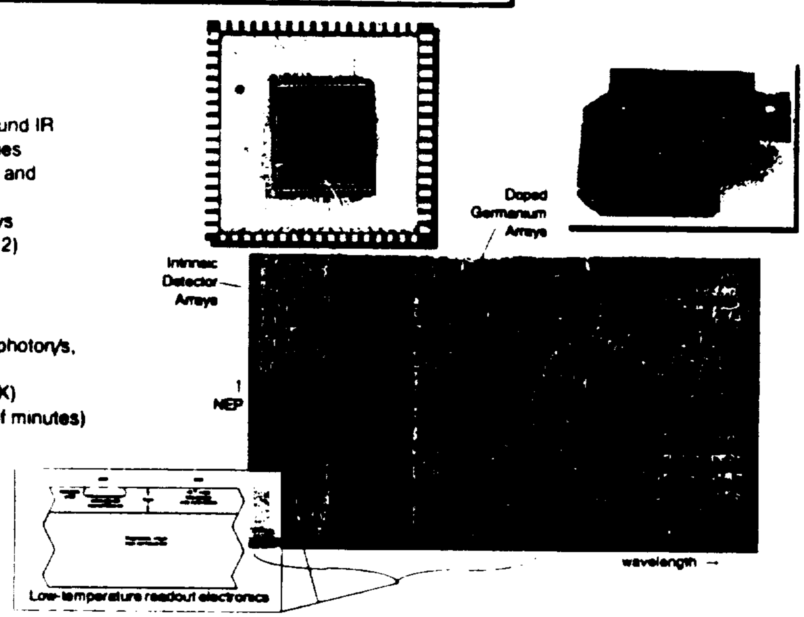
[illegible]

- 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)

[illegible]

- 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)



[illegible]

- 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

[illegible]

- 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

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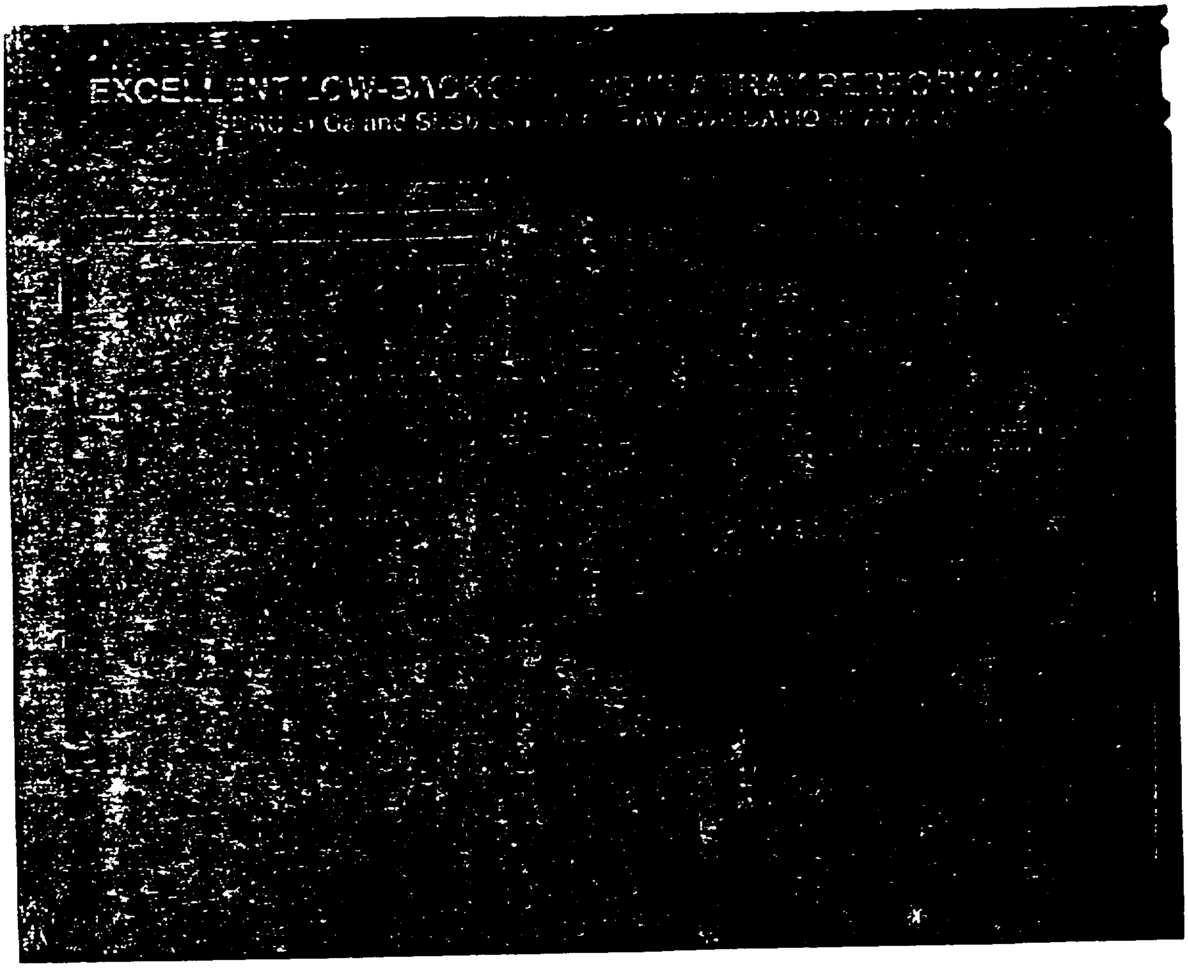

SCIENCE SENSING TECHNOLOGY PROGRAM

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STATE OF THE ART	TODAY	GOALS
SUBMILLIMETER WAVE DETECTORS		
SMMM MIXERS	16 hv / k , 200GHz 40hv / k, 500GHz	10hv/k, 400 - 1200 GHz 10% BW
SMMM LOCAL OSCILLATORS	50μwe, 700 GHz, 300 μwe, 492 GHz	50μw, 400 - 1200 GHz 10% BW
LDR MIXERS	SAME AS ABOVE	15 hv/k, 300 - 3000 GHz BW T.B.D.
LDR FOCAL PLANE ARRAY	NONE	2 x 10 ELEMENTS
LDR LOCAL OSCILLATORS	SAME AS ABOVE	10 mW FOR ARRAYS
SPECTROMETER (GENERIC TO ALL)	500 GHz BW, 1MHz RESOLUTION	SMMM - 10,000 CHANNELS EOS - 20,000 " LDR - 20,000 "

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ORIGINAL PAGE IS
OF POOR QUALITY

SCIENCE SENSING
SUBMILLIMETER SENSORS

OAET

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

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MILESTONES - SUBMILLIMETER WAVE DETECTORS

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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*

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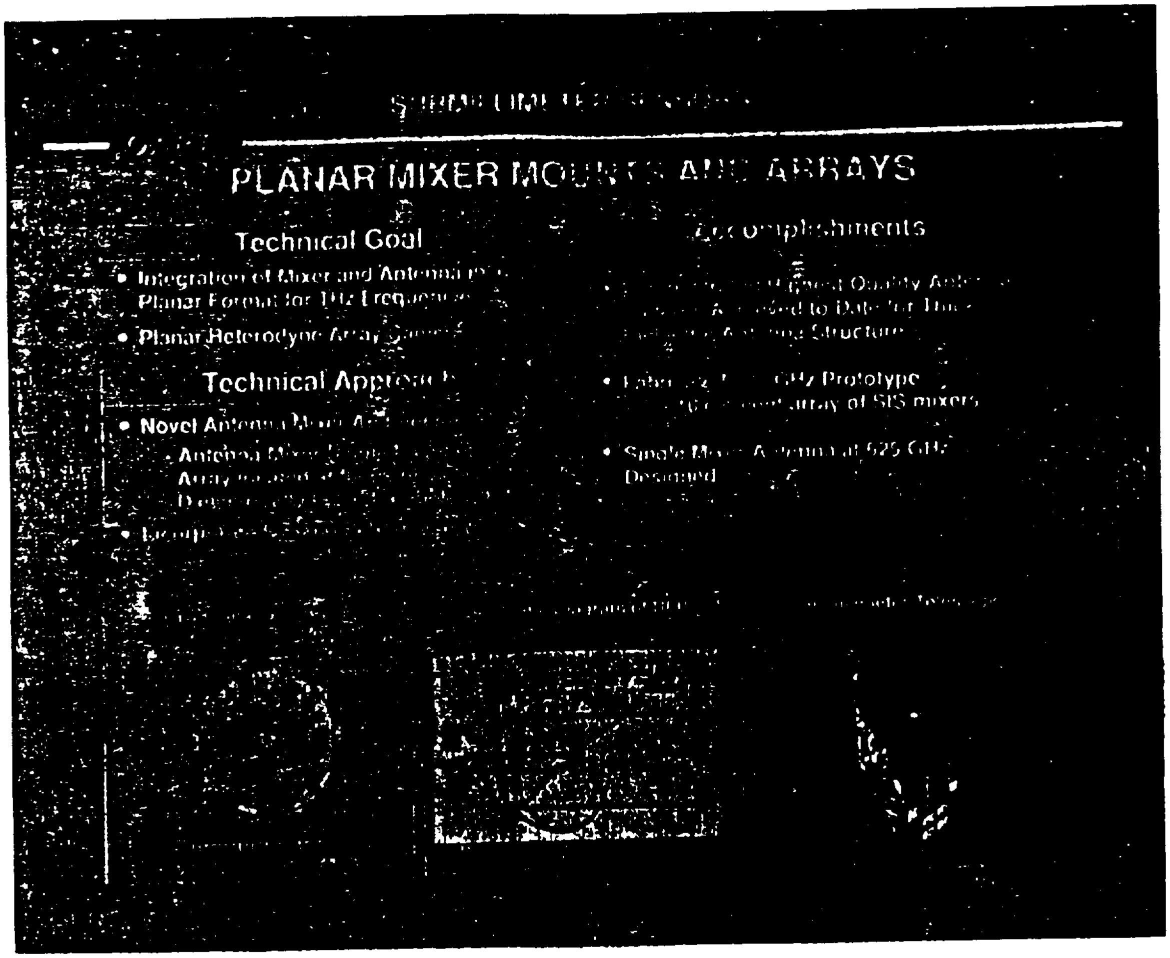

SCIENCE SENSING
LASER SENSING

OAET

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: 0_3 , $C/_2$
- TECTONIC PLATE MOVEMENT
- ICE - PACK MOVEMENT

METROLOGY FOR SPACE VLBI

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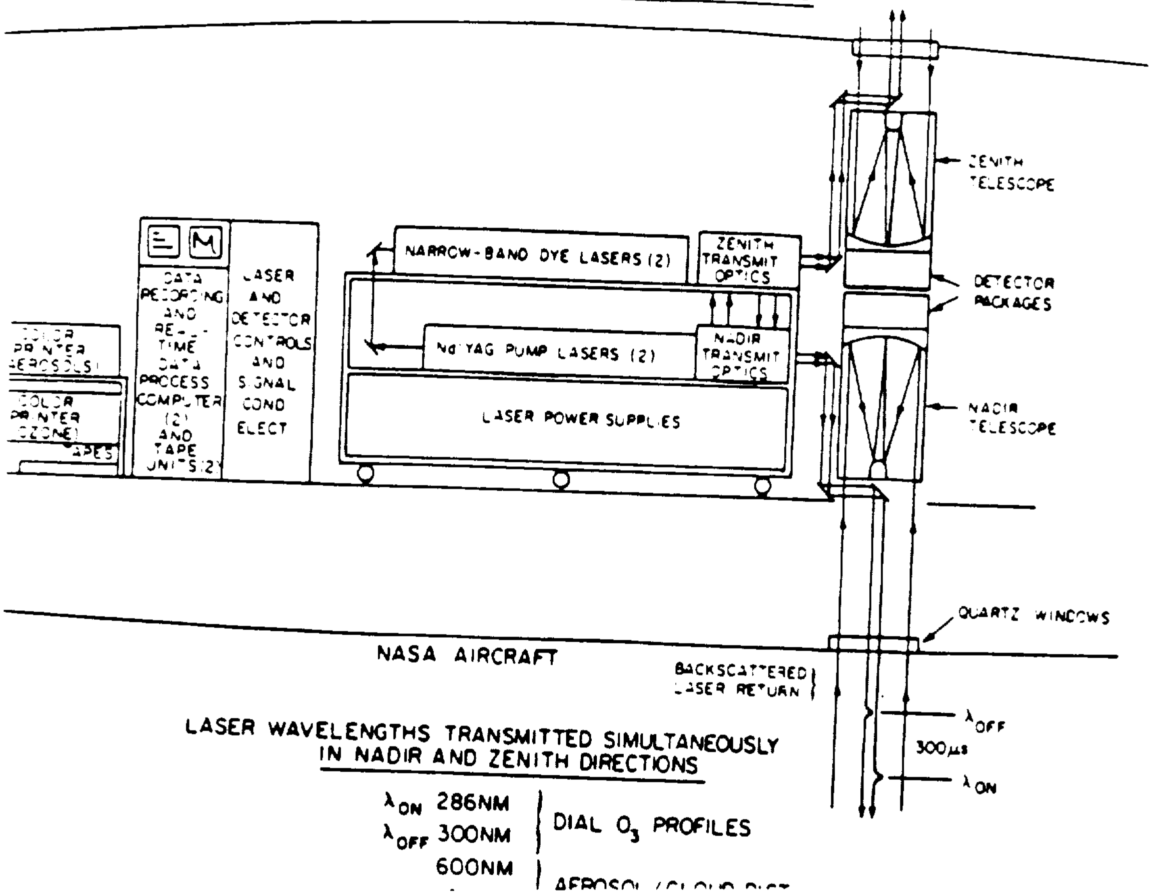
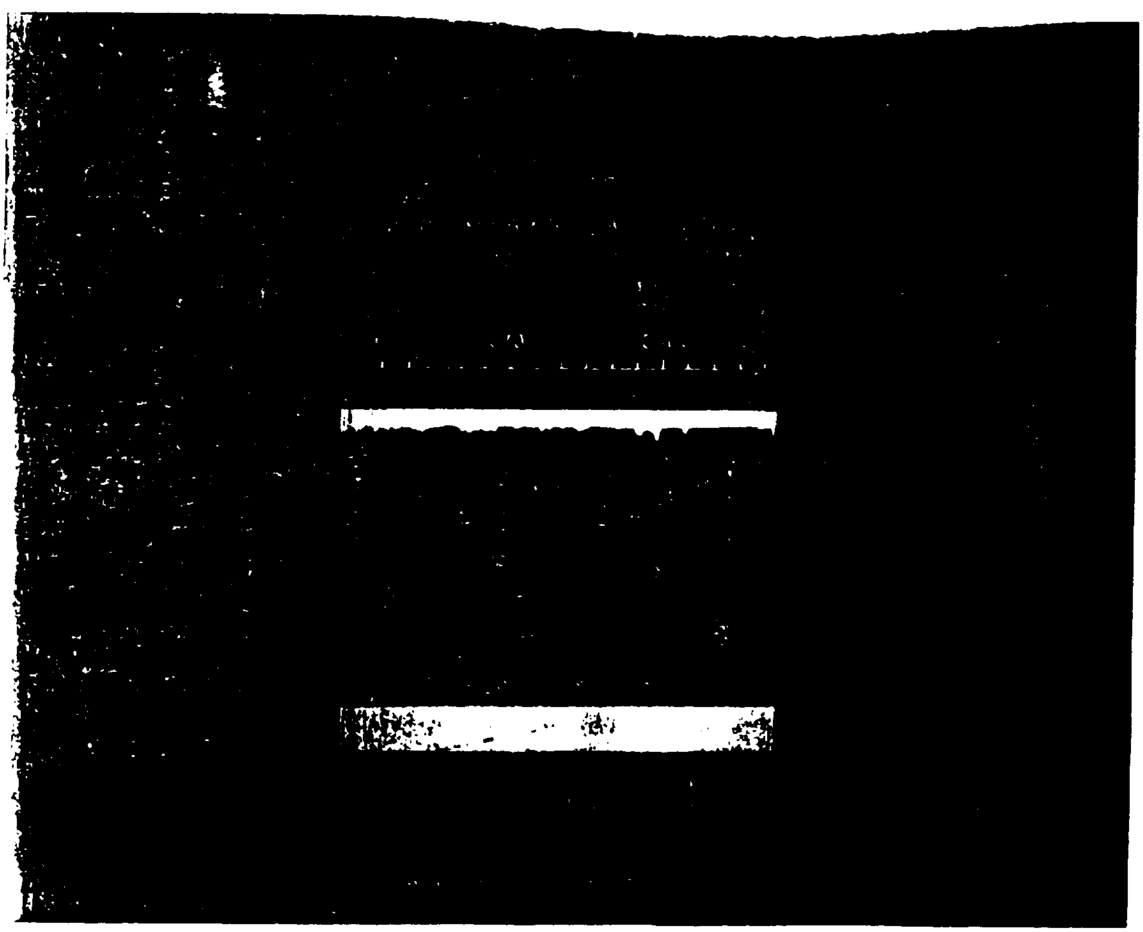
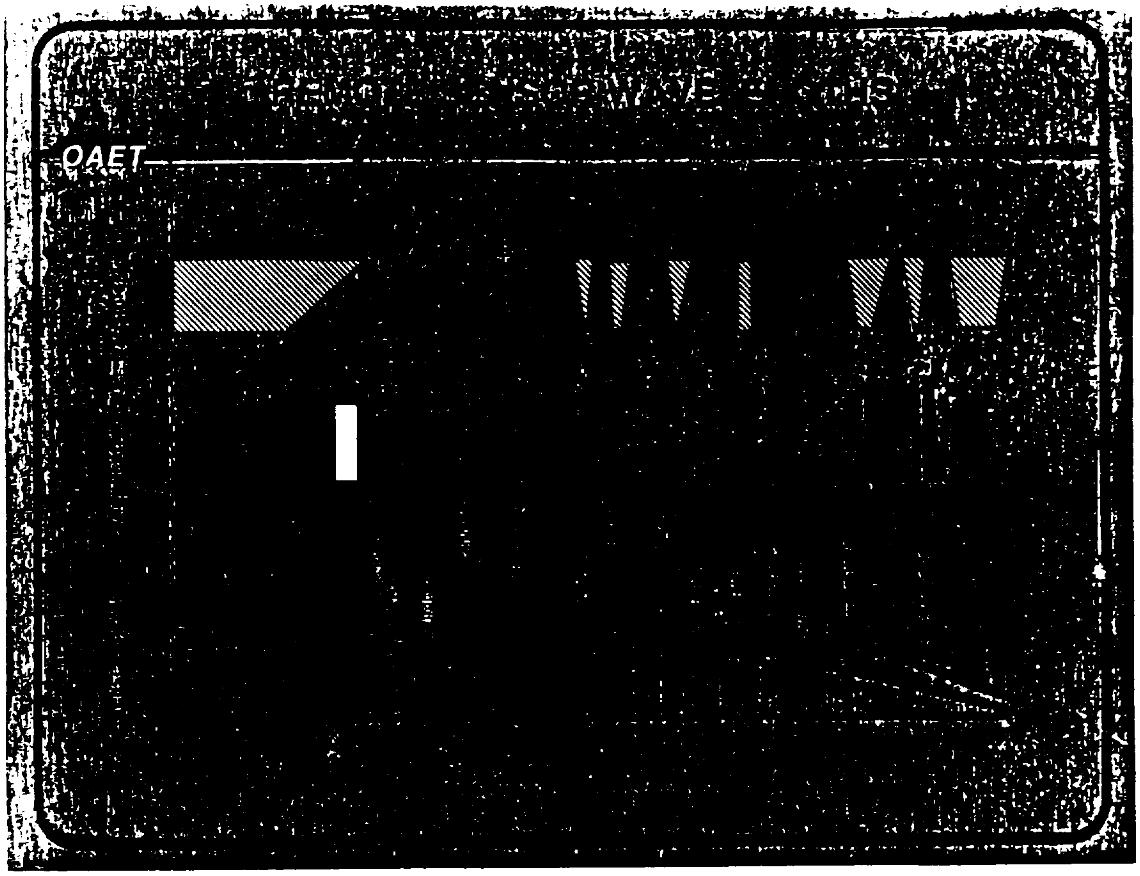
AIRBORNE UV DIAL SYSTEM SCHEMATIC







SPACE QUALIFICATION

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– ISSUES –

WALL PLUG EFFICIENCY

- LIFETIME
- RELIABILITY / STABILITY
- GRACEFUL DEGRADATION

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MILESTONES - LASER SENSING

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<u>ONGOING</u>

- STREAK TUBE RECEIVER - '93
- PROTOTYPE CO_2 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

<u>AUGMENTED</u>

- *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*

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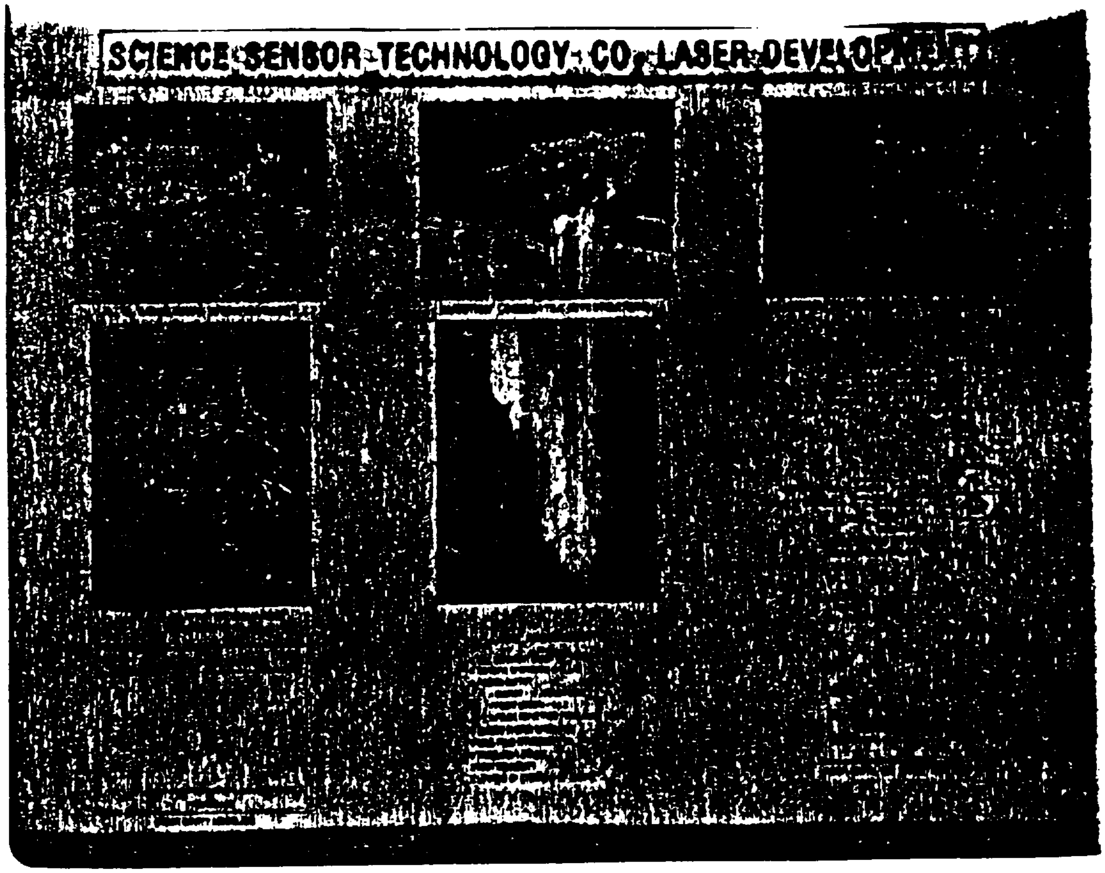

REQUIREMENTS for LASER SUBSYSTEM

REQUIREMENT	CONCEPT WAVELENGTH 9.1 μm	MOTIVATION
ENERGY PER PULSE	10-20 J	SNR
PULSE LENGTH	3 μsec	RANGE/VEL. RESOLUTION
REPETITION RATE	10 pps	COVERAGE
CHIRP	<200 kHz	VEL. RESOLUTION
BANDWIDTH	SINGLE FREQUENCY	VEL. RESOLUTION
BEAM QUALITY	NEAR D.L.	SYSTEM EFFICIENCY
EFFICIENCY (WALL PLUG)	5 %	PRIME POWER
LIFETIME	10 SHOTS	MISSION DURATION
MASS	<150 kg	PLATFORM ACCOMMOD.
OTHER		SPATIAL COHERENCE

LASER CONCEPTS SUMMARY

ITEM	CO_2	[redacted]
PULSE ENERGY > 10 J	DEMONSTRATED	
PRIME ENERGY	ALL SOLID STATE PULSE POWER IN EXISTENCE	
PULSE REPETITION RATE (at REQD. ENERGY)	DEMONSTRATED	
COHERENCE	DEMONSTRATED	
WALL PLUG EFFICIENCY (>5%)	6 - 8 %	
LIFETIME	10^8 COMMERCIALLY	
FREQUENCY STABILITY	DEMONSTRATED	
EYE SAFETY	EYE SAFE	

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 - NG, IMAGING INTERFEROMETER
  - SUBMILLIMETER, LWIR AND X - RAY ASTROPHYSICS MISSION REQUIRE LONG - LIFE 2 - 5 K LOW - VIBRATION COOLERS
    - SMMM, LDR, SMILS, SMMI, 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 FO R & D ON ADVANCED COOLER CONCEPTS
  - DEVELOP COOLER TECHNOLOGY TO PROVIDE NEXT GENERATION COOLERS
  - DEVELOP SUB - KELVIN REFRIGERATION

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MILESTONES - COOLERS AND CRYOGENICS

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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*

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STIRLING COOLER CHARACTERIZATION RESEARCH

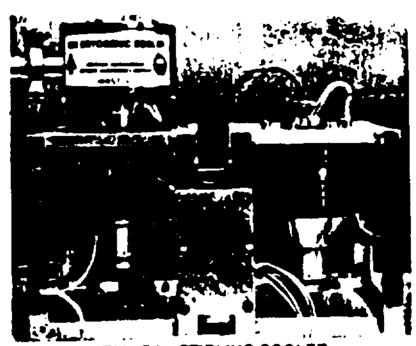
OBJECTIVE: Develop the technology base required to utilize Stirling coolers in sensitive science instruments

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

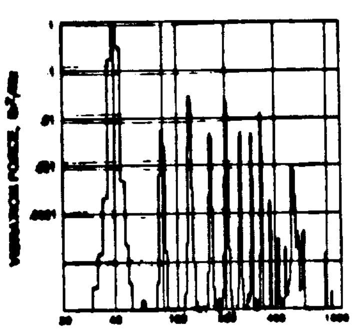
ADVANCED JPL INSTRUMENTATION HAS IDENTIFIED IMPROVED COOLER THERMAL PERFORMANCE



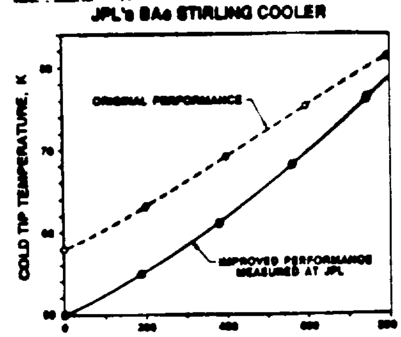
JPL's BAe STIRLING COOLER

JPL TESTING HAS QUANTIFIED THE EXISTENCE OF STRONG COOLER VIBRATION AT FREQUENCIES UP TO 300 Hz

JPL VIBRATION TEST SETUP



VIBRATION FREQUENCY, Hz



HEAT LOAD, mW

SCIENCE SENSING TECHNOLOGY PROGRAM

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LIFETIME	< 1 YR.	> 10 YR.		> 10 YR.
NEED DATA	FLOWN	2000		2000
ACTIVE MICROWAVE SENSING		EOS SAR	TOPOGRAPH RACKOR	RAIN RADAR (GEO)
ANTENNA SIZE	12 m x 4 m	16 x 4 m	2 - 5.5 x 0.4 m	10 m dia.
frequency	1.3, 5.3, 9.6 GHz	1.3, 5.3, 9.6 GHz	35 GHz	35, 94 GHz
Antenna structure	Aluminum	Composite	Composite	Composite
surface accuracy	0.5 cm	0.5 cm	0.1 cm	0.3 cm
Antenna mass	75 kg / m^2	< 20 kg / m^2	< 5 kg / m^2	< 1 kg / m^2
Peak power	9 kw	> 10 kw	> 0.5 kw	> 2 kw
Calibration error	~ 2 - 3 dB	< 1.5 dB, 10° rms	< 1 dB, 3° rms	< 0.5 db
approximate need date	——	1996	1998	1999

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SCIENCE SENSING ACTIVE MICROWAVE SENSORS

OAET

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- BRANDS, POLARIZATION)
    - EOS SCATTEROMETER (SCANSCT)
  - TOPOGRAPHICAL MISSIONS
    - TOPSAT RADAR ALTIMETER (Ka - BAND INTERFEROMETER)
  - METEOROLOGICAL RADAR MISSIONS
    - RAIN RADAR (X-, Ka BAND, LEO)
    - GEOSTRATIONARY 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 UTI[illegible]NG MMIC TRANSMIT / RECEIVE MODULES OPERATING BETWEEN 0.5 - 90 GHz AND I[illegible]OVED FLEXIBILITY WITH ADVANCED DIGITAL CORRELATORS INCORPORAT[illegible] HIGH THROUGHPUT, PRECISION AND IMPROVED FLEXIBILITY WITH ADVANCED POLARIMETRY AND SCANSAR ALGORITHMS.

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MILESTONE ACTIVE MICROWAVE SENSING

OAET

ONGOING

AUGMENTED

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

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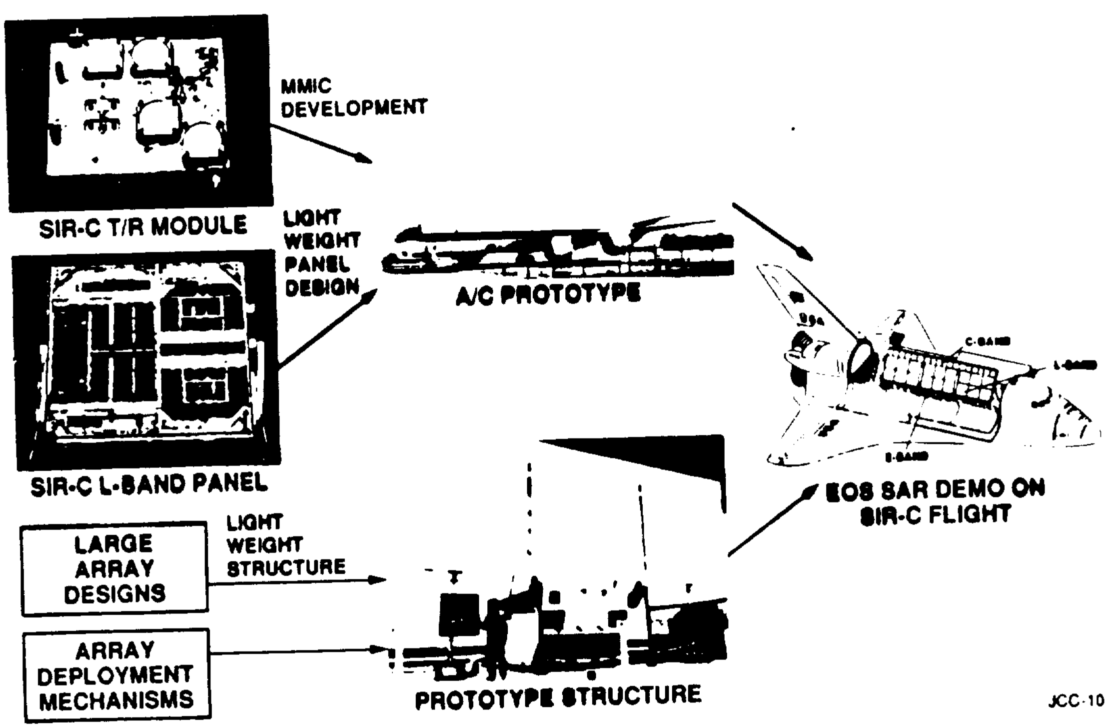
ADVANCED RADAR TECHNOLOGY

JPL EOS SAR ANTENNA TECHNOLOGY



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SCIENCE SENSING TECHNOLOGY PROGRAM

LIFETIME NEED DATA	< 1 YR. FLOWN	> 10 YR. 2000		> 10 YR. 2000
SENSOR ELECTRONICS		EOS SAR	TOPOGRAPH RACKOR	RAIN RADAR (GEO)
Low - temperature operation	15 k using CMOS	2 - 4k		
Low read noise	3 - 5 electron rms in CCD's 30 electron rms in IR switch array munets	1 electron rms		
Large array size	256 x 256 (IR), 2048 x 2048 (CCD)	$10^4 \times 10^4$		
High throughput	0.01 pixels / s	> 100 FPS		
Low - power VHSIC	100 fJ	0.5 fJ		
Array buttability	3 sides	4 sides		

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SCIENCE SENSING
SENSOR ELECTRONICS

TECHNOLOGY NEEDS:

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

BENEFITS:

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

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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*

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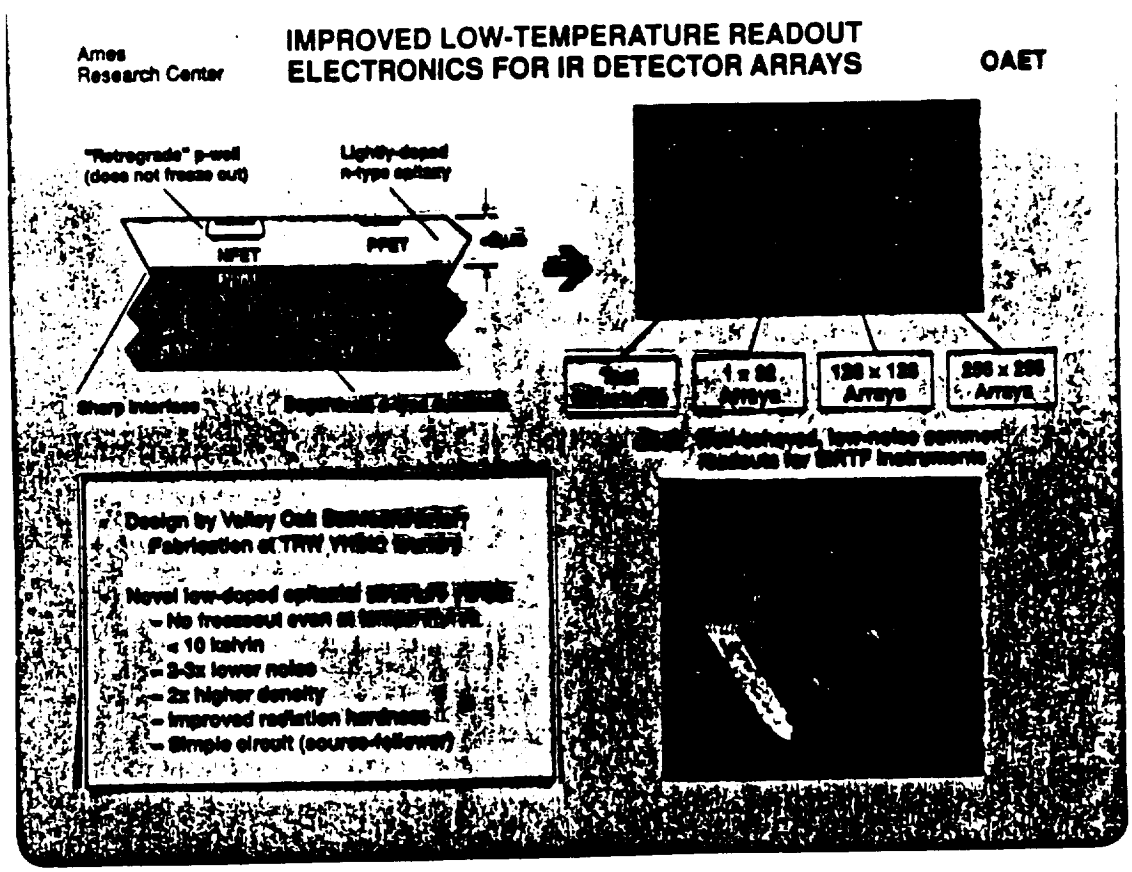

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SCIENCE SENSING TECHNOLOGY PROGRAM

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LIFETIME NEED DATA	< 1 YR. FLOWN	> 10 YR. 2000		> 10 YR. 2000
PASSIVE MICROWAVE SENSING		EOS SAR	TOPOGRAPH RACKOR	RAIN RADAR (GEO)
Precision membrain reflector antenna:				
Diameter	15 m	40 m		
Frequency	up to 12 GHz	5 - 50 GHz		
Low - noise amplifiers (freq)	118 GHz	up to 220 GHz		
Low loss MMIC components	118 GHz	10 - 220 GHz		
Synthetic aperture radiometry	L - band	1 - 6 GHz		
Precision membrain deflector antenna technology	< 40 GHz	10 - 220 GHz		

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SCIENCE SENSING
PASSIVE MICROWAVE SENSING

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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 FRONG-END SENSITIVITIES
- IMPROVED ACCURACY OF MEASUREMENTS
  - DEVELOP IN-SPACE CALIBRATION METHODOLOGY
  - IMPROVED RADIOMETER FRONT-END SENSITIVITIES

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MILESTONES - PASSIVE MICROWAVE SENSING

OAET

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*

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SCIENCE SENSING TECHNOLOGY PROGRAM

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LIFETIME NEED DATA	< 1 YR. FLOWN	> 10 YR. 2000		> 10 YR. 2000
		EOS SAR	TOPOGRAPH RACKOR	RAIN RADAR (GEO)
SENSOR OPTICAL SYSTEM				
Modelling / analysis	Inadequate	stray light, defraction, analysis		
Metrology at nanometer laser	> nanometer level	nanometer level and below		
Sensor optics components	Inadequate	advanced gratings, filters, binary and holographic, phase conjugate optics, fiber optics		
Calibration	changes	long - term stability in flight		

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SCIENCE SENSING
SENSOR OPTICAL SYSTEMS

OAET

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

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MILESTONES - SENSOR OPTICAL SYSTEMS

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ONGOING

AUGMENTED
- *INTERFEROMETER BEAM COMBINERS - '98*
- *STRAY LIGHT - '03*
- *TUNABLE FILTERS - '04*
- *INNOVATIVE OPTICS - '04*
- *INSTRUMENT METROLOGY - '04*
- *GRATING - '05*
- *OPTICAL COMPONENTS - '05*

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SCIENCE SENSING TECHNOLOGY
OTHER EFFORTS/ACTIVITIES

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

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SCIENCE SENSING TECHNOLOGY
INTERACTIVE ACTIVITIES

OAET

- 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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SCIENCE SENSOR TECHNOLOGY
FOCUSED PROGRAM FUNDING

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TECHNOLOGY AREA		FY '92	FY '93	FY '94	FY '95	FY '96	FY '97
DIRECT DETECTORS	BASELINE	5.2	5.8	6.1	3.0	2.7	2.8
	AUGMENTATION	—	2.8	3.6	7.9	7.3	7.3
SUBMILLIMETER WAVE DETECTORS	BASELINE	1.3	1.4	1.5	0.7	0.6	0.6
	AUGMENTATION	—	5.6	6.1	7.1	7.7	7.8
LASER SENSING	BASELINE	3.2	3.6	3.8	1.9	1.8	1.9
	AUGMENTATION	—	5.0	5.8	8.9	9.2	12.4
COOLERS AND CRYOGENICS	BASELINE	3.8	4.3	4.5	2.2	2.0	2.1
	AUGMENTATION	—	4.2	5.4	7.9	8.3	10.6
ACTIVE MICROWAVE SENSING	BASELINE	—	—	—	—	—	—
	AUGMENTATION	—	1.3	1.7	2.0	2.0	4.3
SENSOR ELECTRONICS	BASELINE	—	—	—	—	—	—
	AUGMENTATION	—	1.5	2.7	3.4	4.1	6.0
SENSOR OPTICS *	BASELINE	—	—	—	—	—	—
	AUGMENTATION	—	—	—	5.0	9.4	13.5
PASSIVE MICROWAVE * SENSING	BASELINE	—	—	—	—	—	—
	AUGMENTATION	—	4.0	7.0	12.0	16.0	16.5
TOTALS	3X (AUGMENT)	13.5	35.5	41.2	45.0	45.7	55.8
	STRATEGIC	0	45.8	56.5	73.8	85.9	92.8

* STRATEGIC PROGRAM

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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

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
    - •REFINE AND OPTIMIZE PRESENTLY-EMERGING TECHNOLOGIES (e.g., HgI_2, HPGe for high-energy; InSb for SWIR; CCDs for UV/VIS/NIR)
    - •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

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

STATE-OF-THE-ART ASSESSMENT

Spectral Band	Existing Technology	Status/Limitations
Gamma- and X-ray	Discrete detectors -High-purity Ge and Si -Mercuric iodide (HgI_2) -Proportional counters Scintillator-microchannel plates	No imaging capability Low quantum efficiency Limited energy resolution Small detector size
UV and visible	Si CCDs ($\geq$2048 x 2048) Microchannel plates ($\geq$1024 x 1024)	Limited QE Limited spectral coverage No solar rejection Radiation susceptibility
SWIR (1-5 μm)	HgCdTe and InSb arrays (256x 256) PtSi Schottky diode arrays (512x512)	Limited array size Low quantum efficiency Low temperature required
LWIR (5-30 μm)	HgCdTe to ~15 μm Si:As IBC arrays (128 x 128) for T<12 K	Limited spectral response Low temperature required Low yield
Far IR (30-1000 μm)	Discrete bolometer arrays Bulk Ge:x photoconductors	No integrated arrays Poor QE No mux'ing for bolometers Radiation susceptibility
Broadband (1-1000 μm)	Pyroelectrics Thermopiles	Poor QE Poor frequency response Small discrete arrays

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
- -HgI_2 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 nipi 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_c 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

DIRECT DETECTORS

FOCUSSED TECHNOLOGY PERFORMANCE OBJECTIVES

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

MISSION REQUIREMENT	CURRENT SOA	REQUIRED CAPABILITY
Energy Res'n (FWHM) (eV)	75	20
Useable Range (keV)	0.4 - 4	0.25 - 10
Dimensions (mm^2)	7.5 x 7.5	30 x 30
Readout Noise (e^-)	1.5	<0.5
Effective Pixel Size (µm)	30 x 30	5 x 5
Radiation Resistance	Low	>15 krads

SPACE SCIENCE TECHNOLOGY. SCIENCE SENSING

DIRECT DETECTORS

FOCUSSED TECHNOLOGY PERFORMANCE OBJECTIVES

Example 2: UV-Visible Detector (Si CCD Array for NGST)

MISSION REQUIREMENT	CURRENT SOA	REQUIRED CAPABILITY
Array Size	800 x 800 (WF/PC I)	≥15,000 x 15,000
QE (0.1 - 0.4 µm) (%)	>15	>80
QE (0.4 - 1 µm) (%)	>15	>80
Well Capacity (e^-)	3×10^4	1×10^5
Pixel Size (µm)	15	5
Visible Blindness	$<10^{-4}$	$<10^{-9}$
Read Noise (e^-)	10	0.1
Operating Temp (°C)	-95	20
Mosaic Capability	No	Buttable for 2-d mosaic

DIRECT DETECTORS

FOCUSSED TECHNOLOGY PERFORMANCE OBJECTIVES

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

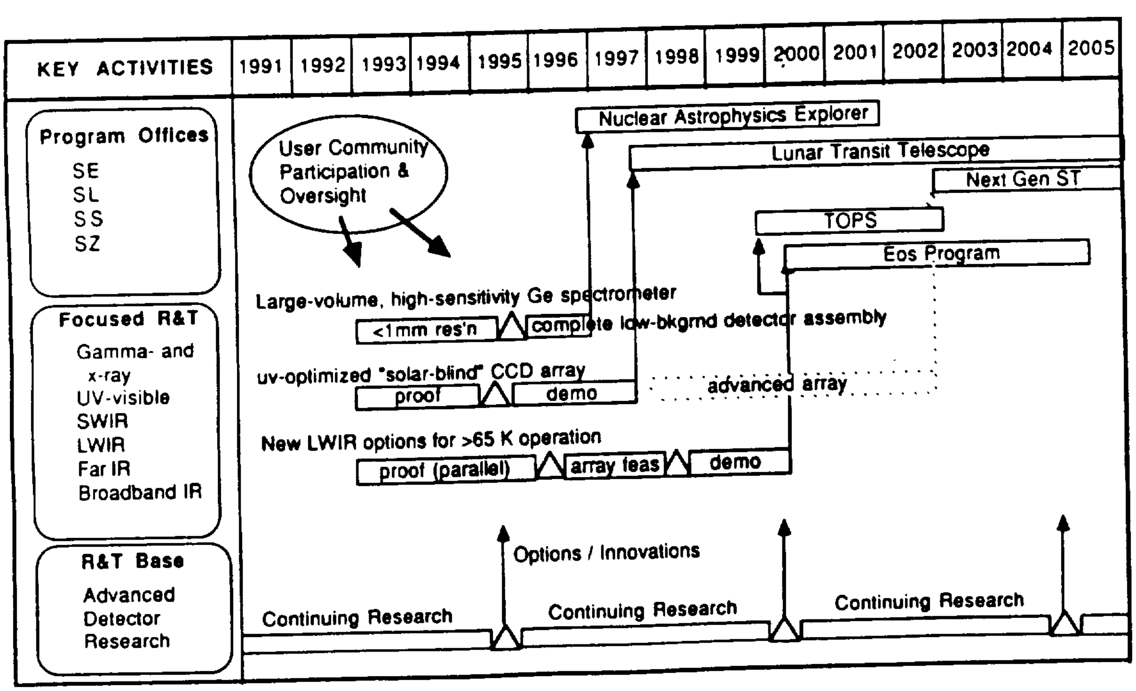
MISSION REQUIREMENT	CURRENT SOA	REQUIRED CAPABILITY
Detector Type	Ge:Ga bulk photoconductor	Ge:Ga IBC array
Spectral Range (μm)	60 - 120	35 - 200
Array Format	1 to 3 x 32	32 x 32
Array Type	Stacked linear modules	Planar, integrated
Operating Temperature (K)	2	2
Readout Temperature (K)	≥25	2
Noise Equivalent Power (W/√ Hz); 1 s integration	2×10^{-18}	2×10^{-19}
Quantum Efficiency (%)	5	≥40
Radiation Susceptibility	High	Low

SCIENCE SENSOR TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

TECHNOLOGY ROADMAP/SCHEDULE

Three Examples



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 HgI_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; AlGaAs/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 PRIORITIZATION:

Focused Program

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

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

DIRECT DETECTORS

FLIGHT EXPERIMENTS

(None)

DIRECT DETECTORS

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

Subelements	FY92	93	94	95	96	97	Total
A. Gamma - and X-ray	0.2	0.3	0.4	0.2	0.2	0.2	1.5
B. UV and visible							0
C. SWIR	0.3	0.3	0.4	0.2	0.1	0.2	1.5
D. LWIR	3.2	3.7	3.7	1.6	1.6	1.6	15.4
E. Far IR	1.5	1.5	1.6	1.0	0.8	0.8	7.2
F. Broadband IR							0
Ongoing -- Subtotal	5.2	5.8	6.1	3.0	2.7	2.8	25.6
A. Gamma- and X-ray		0.9	1.0	2.0	2.0	2.0	7.9
B. UV and visible		0.2	0.4	1.1	1.0	1.0	3.7
C. SWIR		0.1	0.3	0.8	0.7	0.7	2.6
D. LWIR		0.8	0.9	2.1	1.7	1.7	7.2
E. Far IR		0.5	0.6	1.1	1.1	1.1	4.4
F. Broadband IR		0.3	0.4	0.8	0.8	0.8	3.1
Augmention – Subtotal	0	2.8	3.6	7.9	7.3	7.3	28.9
Total	5.2	8.6	9.7	10.9	10.0	10.1	54.5

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

Presented by
M. A. Frerking
JPL

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

AGENDA

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

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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

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SUBMILLIMETER SENSORS

TECHNOLOGY NEEDS

MISSION SET

• Astrophysics	Frequency	New Start
-SMIM	400-1200 GHz	1997
-LDR	300-3000 GHz	2002
-Lunar Interferometer	300-3000 GHz	2004
• Earth Remote Sensing		
-EOS MLS	640 GHz	1996
-EOS MLS 2nd Generation	1800 GHz	2000

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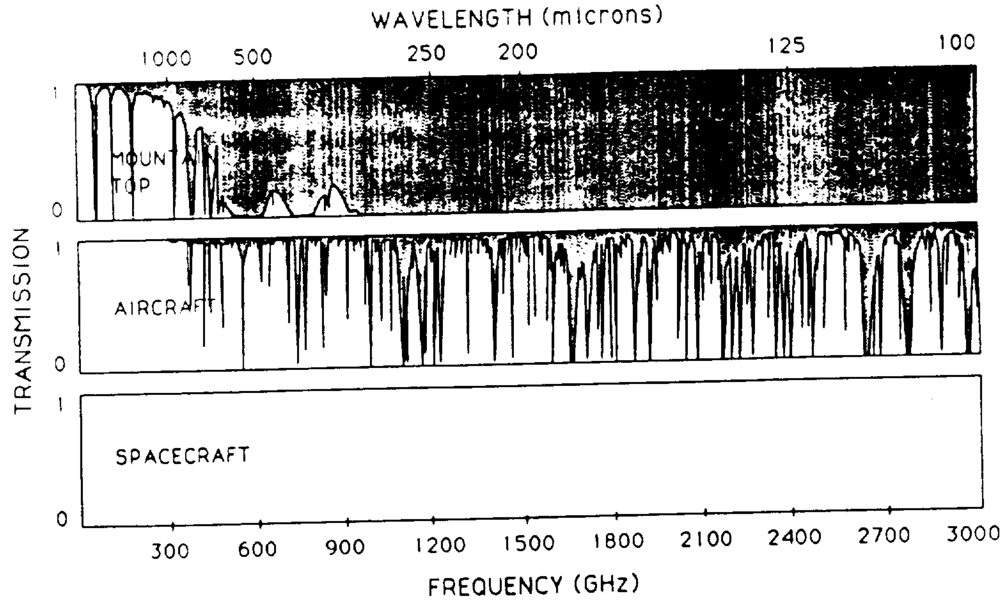
SUBMILLIMETER SENSORS

ATMOSPHERIC TRANSMISSION



Submillimeter Wavelength: 1000 to 100 μm or 300 to 3000 GHz

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SUBMILLIMETER SENSORS

SUBMILLIMETER INTERMEDIATE MISSION (SMIM)

- 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

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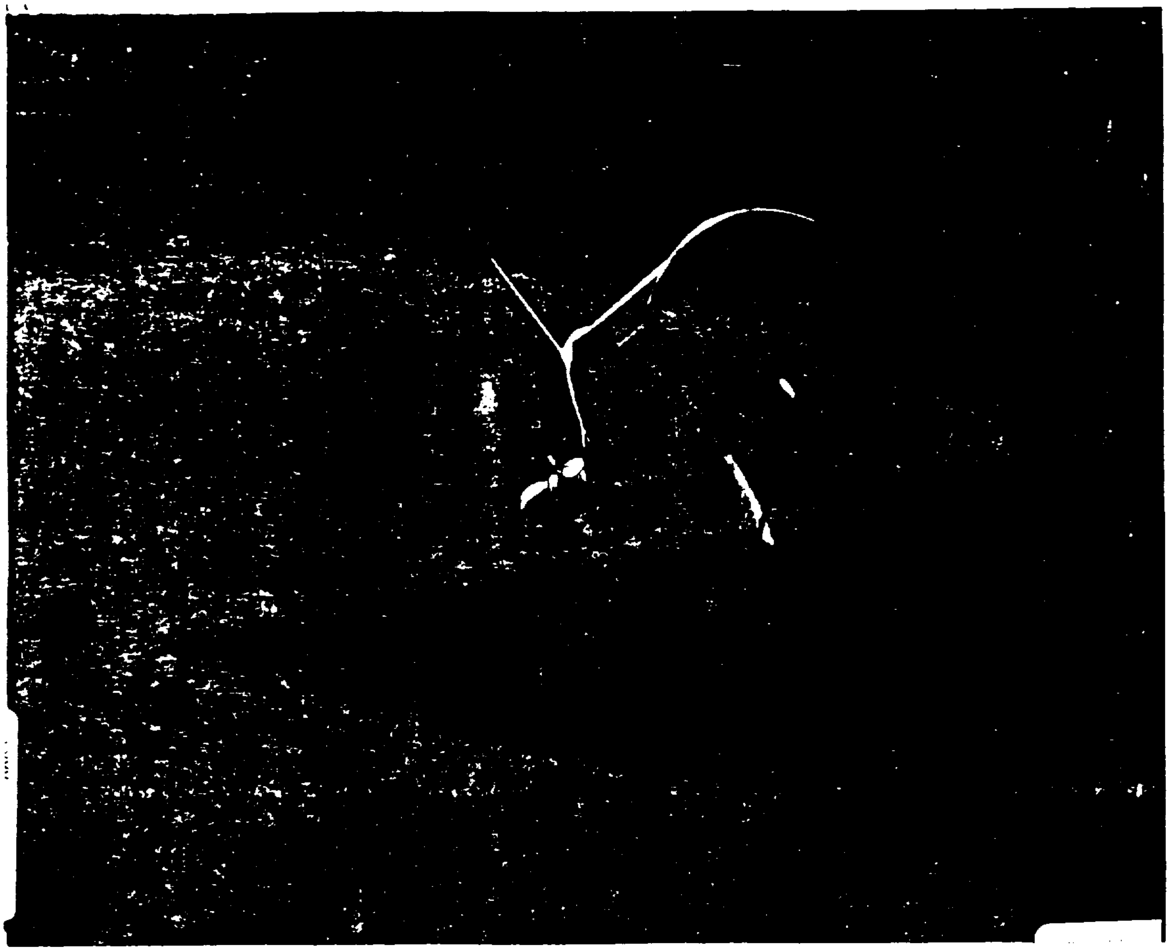

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TYPICAL SPECTRUM FROM SMIM

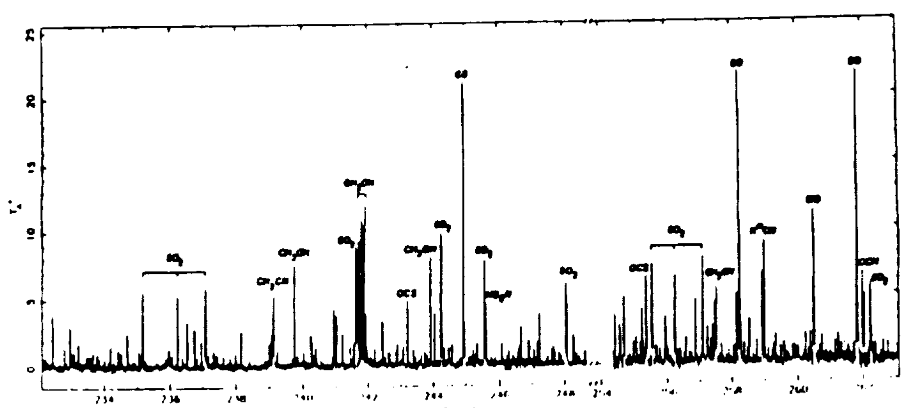

Figure 1.3. A compressed view of the OVRO spectral line survey of OMC-1.

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SUBMILLIMETER SENSORS

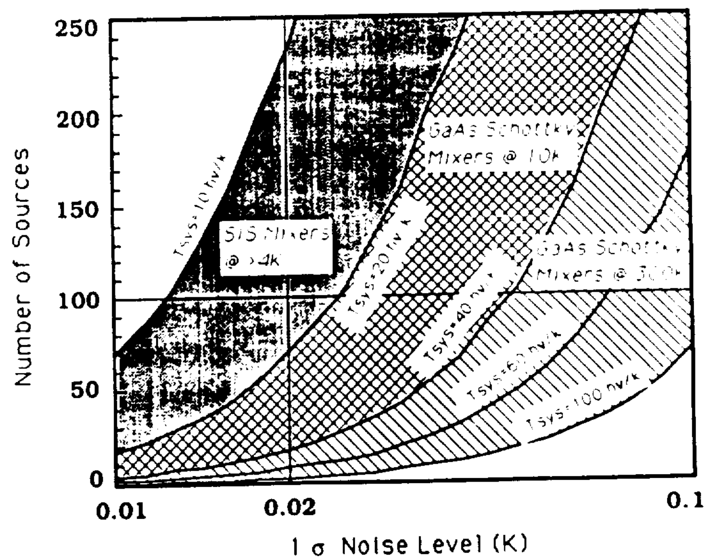
SENSITIVITY TRADE FOR SMIM

Objective:
100 sources

Sensitivity:
0.02 K noise

Receiver figure of merit: T_{sys}

Need:
Tsys < 20 hv/k



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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

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

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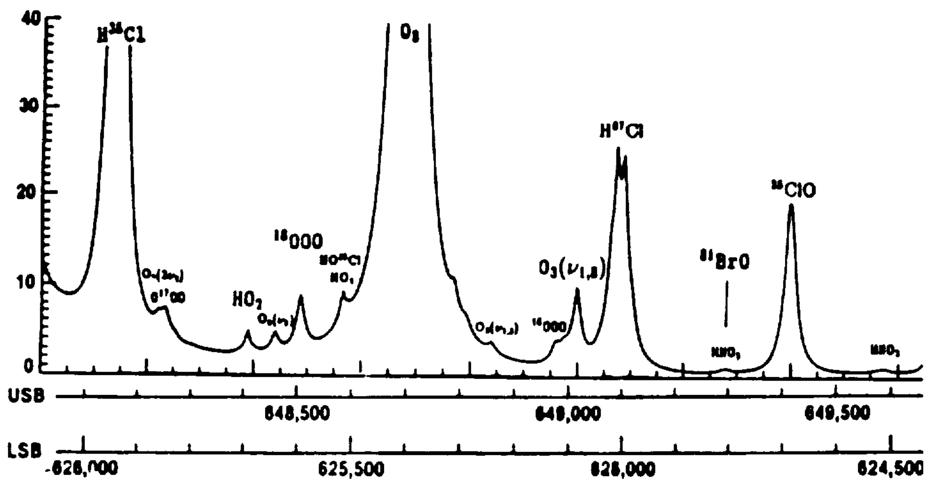
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TYPICAL SPECTRUM FOR Eos-MLS



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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TECHNOLOGY CHALLENGES

ASTROPHYSICS

ASTROTECH 21 ADVISORY GROUP RECOMMENDATIONS

- Identified Four Technology Areas
  - Local oscillator development (frequency agile, broad band)
  - Mixer development (high sensitivity Tsys=10 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

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TECHNOLOGY CHALLENGES

EARTH REMOTE SENSING

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?

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SUBMILLIMETER SENSORS

TECHNOLOGY CHALLENGES

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 tear mission
  - Planar Schottky diodes
- Passively cooled operation (80-130 K)

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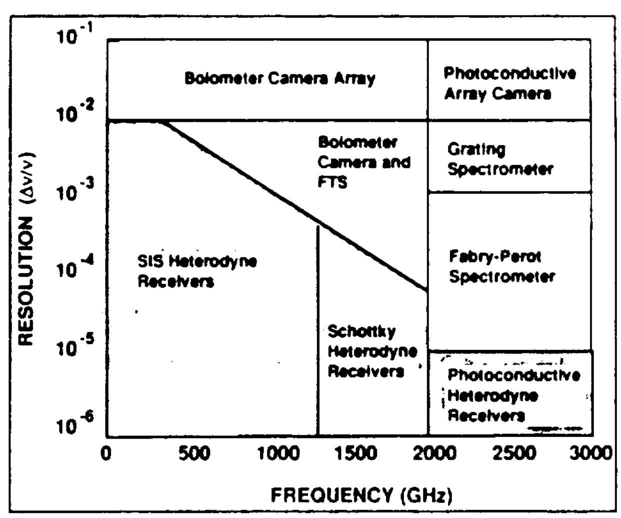
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

Heterodyne Receiver is Instrument of Choice for

- High spectral resolution
- High sensitivity



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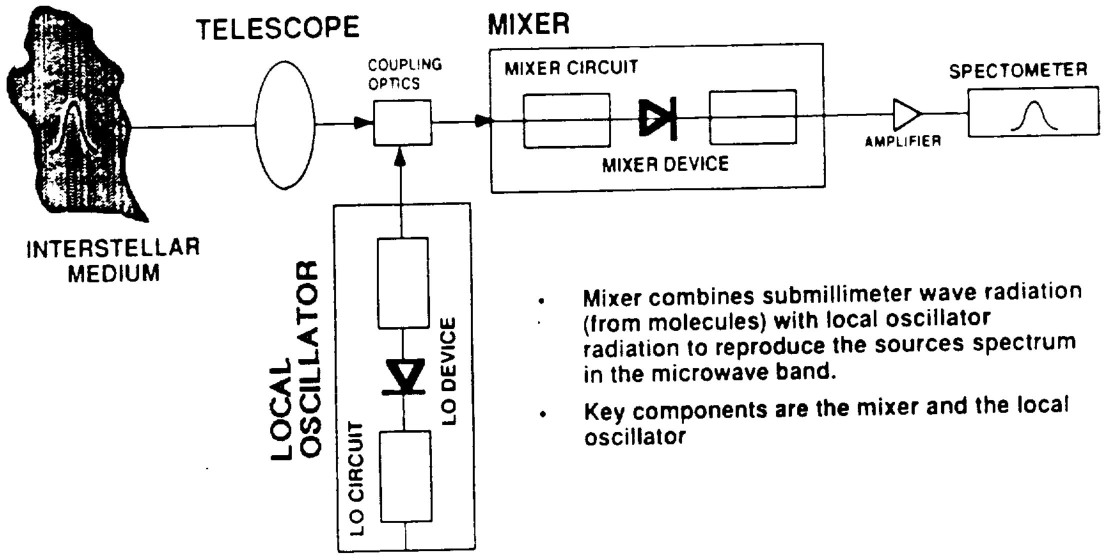
SUBMILLIMETER SENSORS

HETERODYNE RECEIVER SCHEMATIC



- 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

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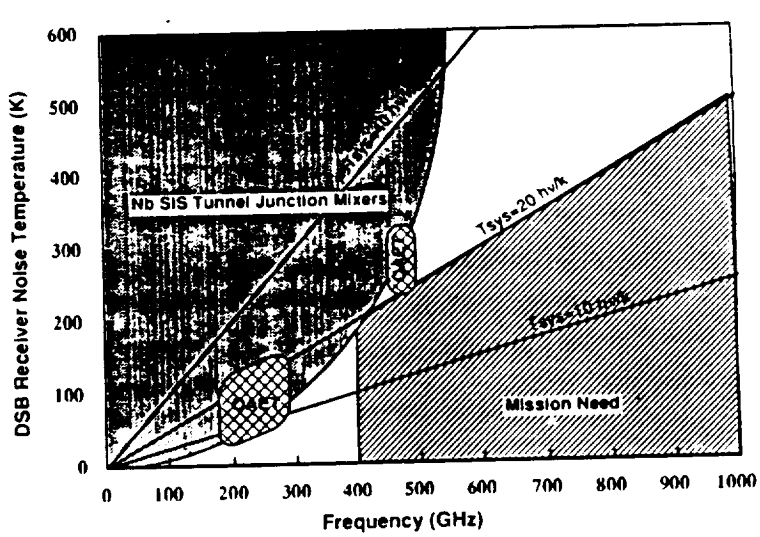
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

STATE OF THE ART ASSESSMENT
SUPERCONDUCTING HETERODYNE MIXERS

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



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SUBMILLIMETER SENSORS

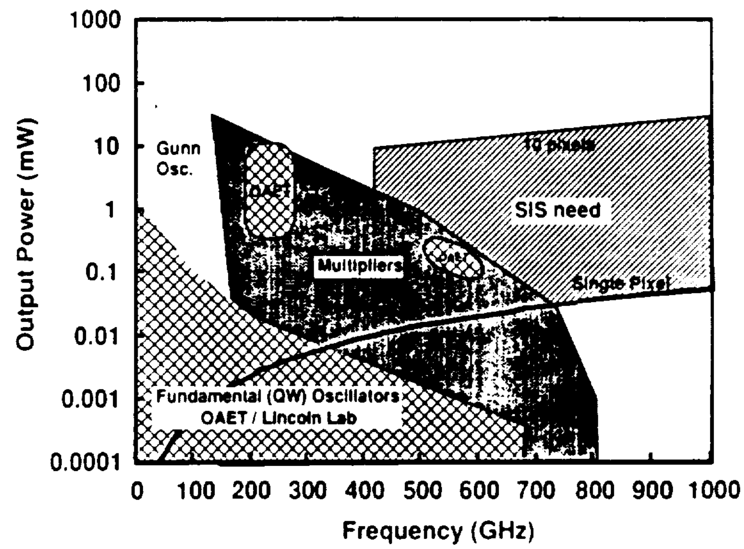
STATE OF THE ART ASSESSMENT

LOCAL OSCILLATORS

Current OAET program has:

a) Developed high performance multipliers

b) Pioneered submm wave fundamental oscillator development using quantum well oscillators



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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

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 ωRC product
  - Circuit: Innovative transmission lines, tuning elements

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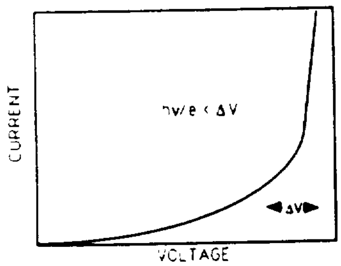
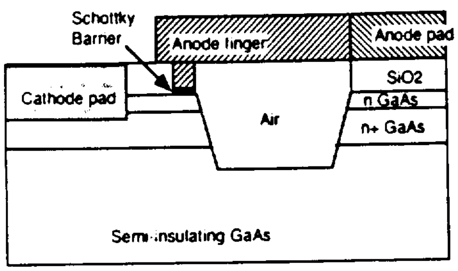
SUBMILLIMETER SENSORS

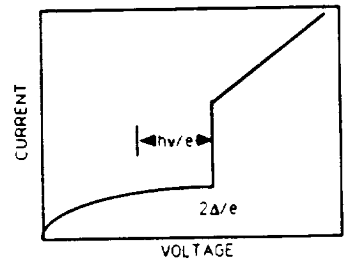
MIXER DEVICES

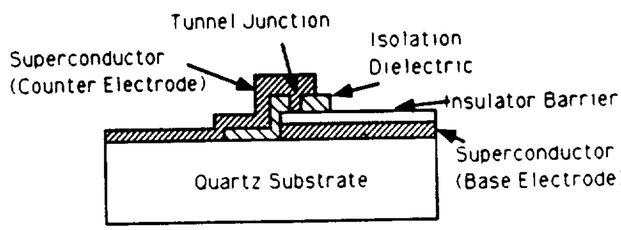
Planar Schottky Diode





Superconductor Insulator Superconductor (SIS) Tunnel Junction





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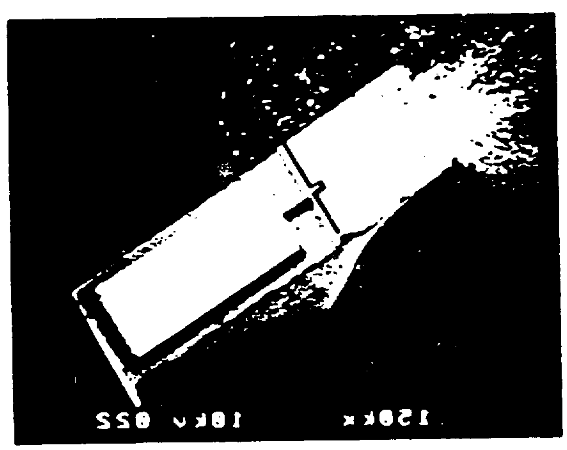
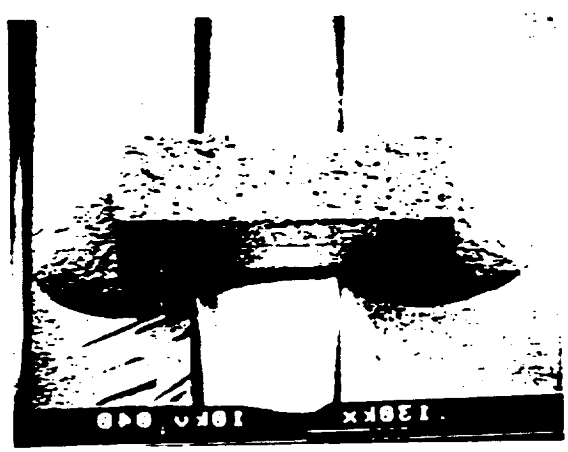
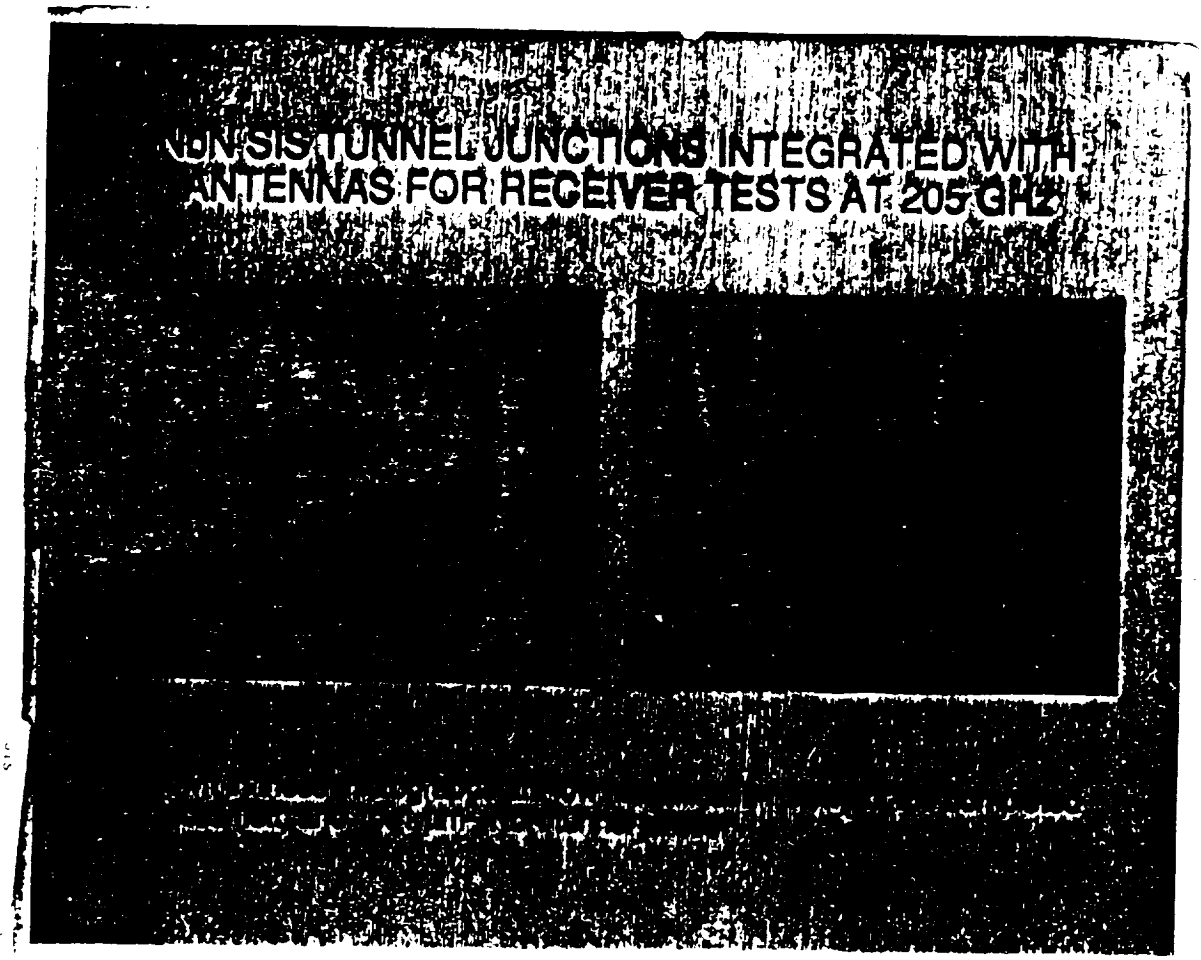




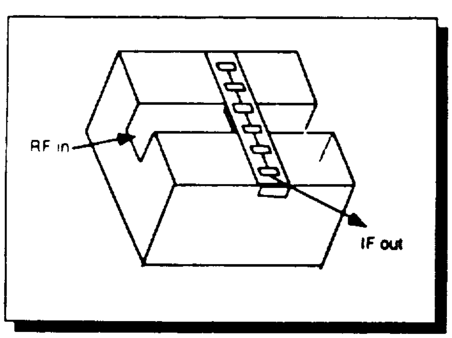


SUBMILLIMETER SENSORS

MIXER CIRCUITS

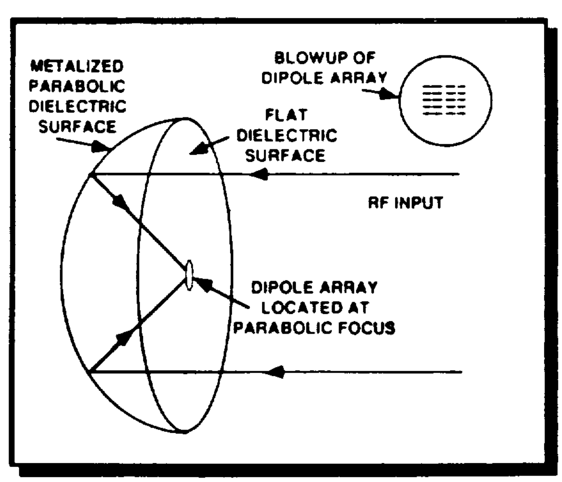
Waveguide Mixer

Machined Dimensions < λ



Planar Mixer Array

Machined Dimensions > λ



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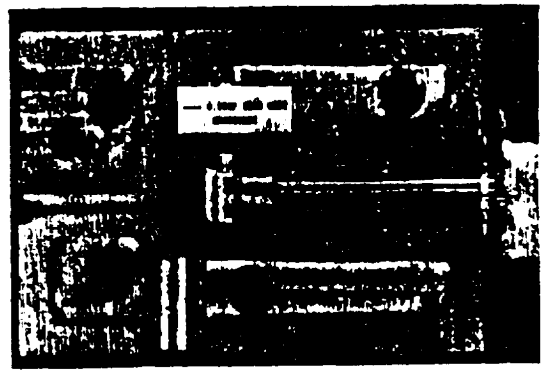
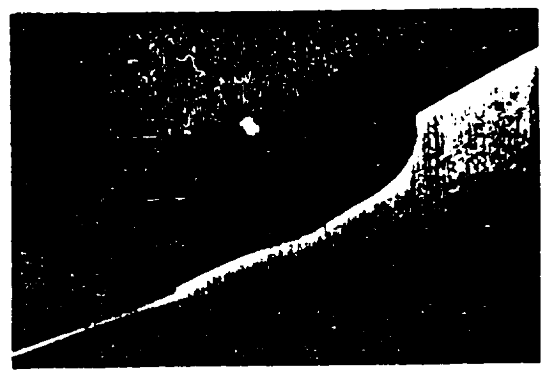
OAET

SIS MIXER MOUNTS



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



- PLANAR 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 ωRC, high speed materials system
    - Circuit: innovative transmission lines, tuning elements

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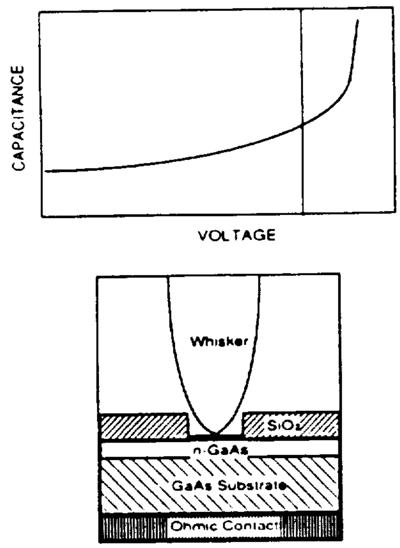
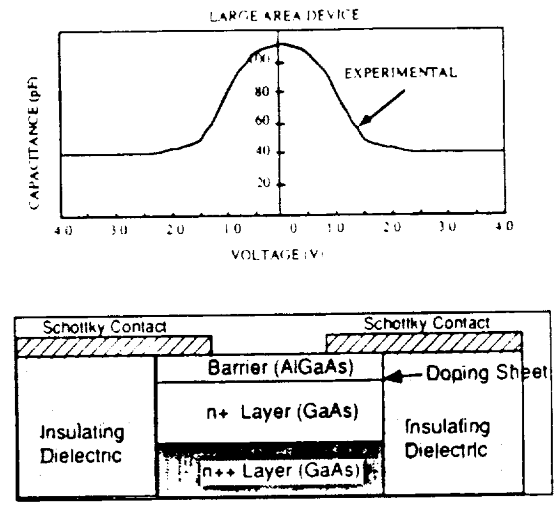
SUBMILLIMETER SENSORS

LOCAL OSCILLATOR DEVICES

GaAs Schottky Varactor



Planar bbBNN Varactor



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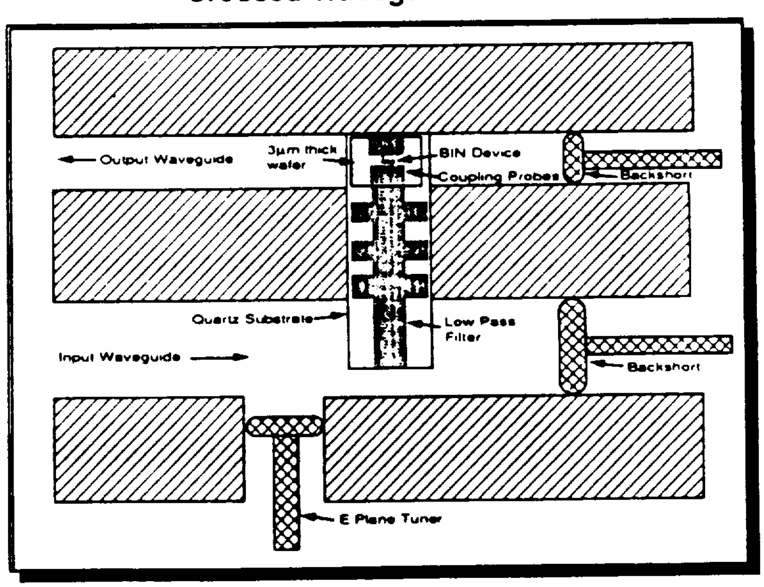
SUBMILLIMETER SENSORS

LOCAL OSCILLATOR CIRCUITS

Crossed Waveguide Mount



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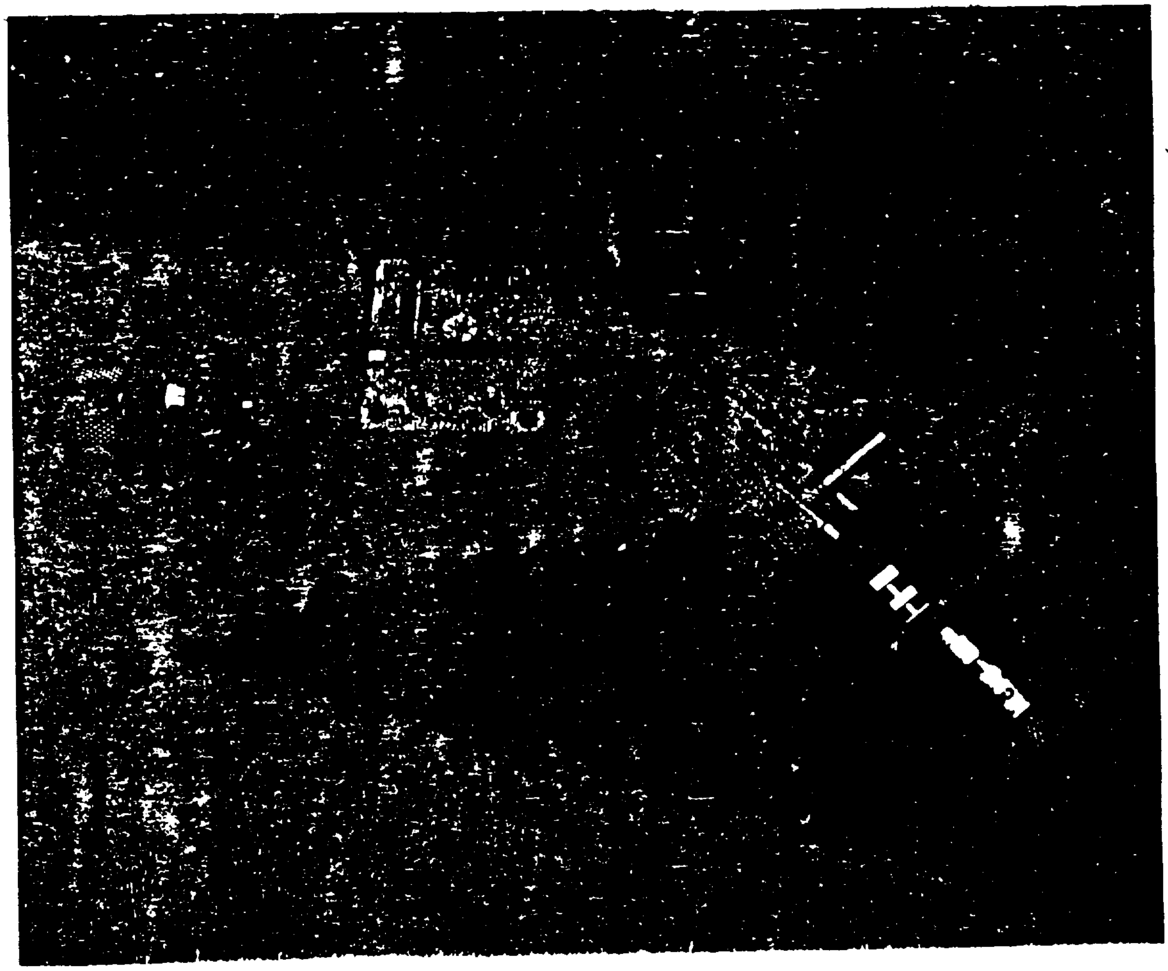

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

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

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SUBMILLIMETER SENSORS

TECHNOLOGY PROGRAM OBJECTIVES (details)

Mission Requirement	Current SOA	Objective
SMIM LOs		
Output Power	50μW @ 700 GHz	50μW @ 400-1200 GHz
Bandwidth	2-3%	10%
SMIM Mixers		
Sensitivity	20 hv/k @ 492 GHz	10 hv/k @ 400-1200 GHz
Bandwidth	5%	10%
LDR LOs		
Output power	50μW @ 700 GHz	10 mW for arrays
LDR Mixers		
Sensitivity	20 hv/k @ 492 GHz	10 hv/k @ 300-3000 GHz
LDR Array		
No. of pixels	-	2x10 element

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TECHNOLOGY PROGRAM OBJECTIVES (details)

Mission Requirement	Current SOA	Object
Spectrometer	AOS	AOS
Bandwidth	500 GHz	2-4 GHz
No. of channels	500	10,000 - 200,000
Power/channel	100 mW	10 mW
EOS MLS		
600 GHz mixer	Whiskered GaAs	Planar GaAs
IF Freq / BW	4 GHz / 25%	20 GHz / 50%
Sensitivity	100 hv/k	100 hv/k
1800 GHz mixer	Corner cube, whisker	Planar
Sensitivity	300 hv/k	100 hv/k
1800 GHz LO	Gas laser	TBD

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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

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

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

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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

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

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

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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

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SUBMILLIMETER SENSORS

OTHER NON-NASA DEVELOPMENT EFFORTS

This effort is unique to NASA needs

<u>NASA programs</u>

- OAET Science Sensing Submillimeter Program
  - Goal: Focussed 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: Focussed technology development for mission set
- OAET University Centers of Excellence - Space Terahertz Technology Center at the University of Michigan
  - Goal: Generic technology development

<u>SDIO program (small)</u>

- Superconducting Technology
  - Goal: Superconducting focal plane receiver

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SUBMILLIMETER SENSORS

FUNDING PROFILE

	1992	1993	1994	1995	1996	1997
Baseline ($M)	1.3	1.4	1.5	0.7	0.6	0.6
Augmentation	-	5.6	6.1	7.1	7.7	7.8
Total ($M)	1.3	7.0	7.6	7.8	8.3	8.4

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

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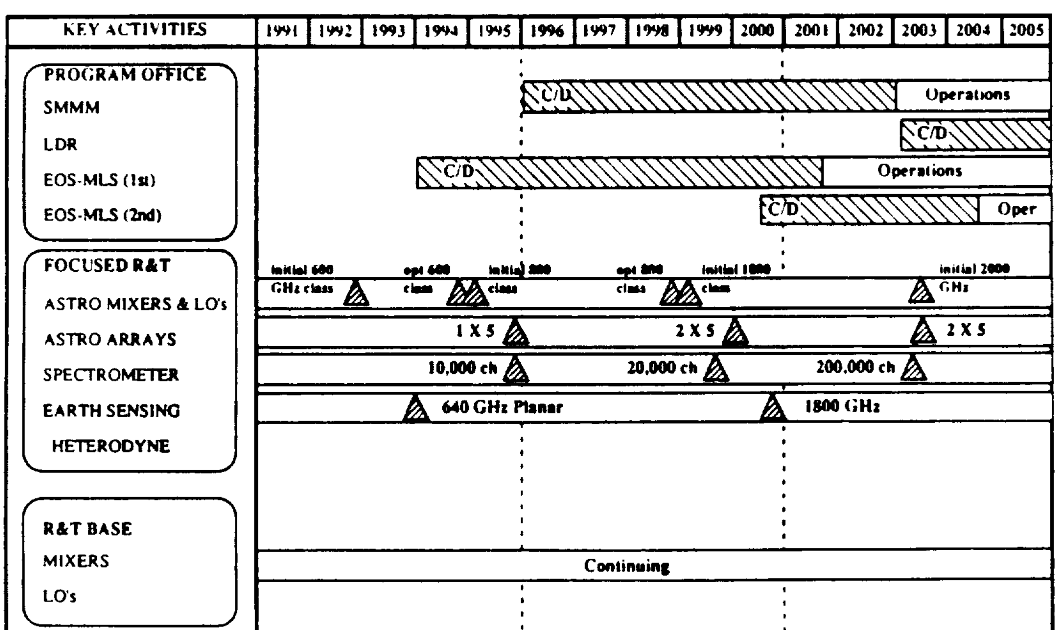
SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SUBMILLIMETER SENSORS

TECHNOLOGY ROADMAP / SCHEDULE



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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
  - $5 \cdot 10^9$ 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
  - $3.3 \cdot 10^9$ SHOTS PULSED
  - 30,000 HOURS CONTINUOUS WAVE
  - FACTOR OF 3 IN DAMAGE THRESHOLD, UV OPTICS
- TUNING
  - 0.68 - > 1.0 μm $Ti{:}Al_2O_3$
  - 0.72 - 0.81 μm $Cr{:}BeAl_2O_4$
  - 2.5 - 5.4 μm $AgGaSe_2$ OPO
  - 2.06 - 2.10 Ho:YLF, Ho:YAG

CURRENT PROGRAMS

- DOPPLER LIDAR
  - CO_2 GAS LASER
  - Ho:YLF SOLID-STATE LASER
- DIAL IN NEAR-INFRARED
  - Ti:Al_2O_3
  - Cr:$BeAl_2O_4$
- DIAL IN MID-INFRARED
  - OPTICAL PARAMETRIC OSCILLATOR
  - RAMAN SHIFTING
- LASER RANGING
- DIODE DEVELOPMENT
  - SEED LASERS
  - DIODE LASER ARRAYS

AUGMENTED PROGRAMS

Instrument Demonstration

• Doppler LIDAR	LAWS
• DIAL/Eyesafe DIAL	EAGLE
• Ranging/Altimetry	GLRS

Technology Development

• In-Situ Lasers	Tunable, Single Wavelength
* High-Energy Optics	Damage Resistant Optics
• Receiver Technology	Arrays/Amplifiers
• Models/Spectroscopy	Laser Design/New Materials
• Laser Diode Materials	New Materials/Wavelength
* Scanning Lidar	Develop Scanning

*NEW PROGRAMS

OBJECTIVE: GLOBAL WIND-SPEED MEASUREMENT

DOPPLER LIDAR	CO_2 LASER	Ho:YLF LASER
Energy/Pulse	15 J	5-15 J
Pulse Repetition Frequency	10	10
Linewidth	< 0.2 MHz	< 1.0 MHz
Pulselength	~ 3.0 μsec	> 0.6 μsec
Wavelength	9.1 μm	2.1 μm
Lead Center	MSFC	LaRC

OBJECTIVE: GLOBAL MEASUREMENT OF ATMOSPHERIC CONSTITUENTS

DIAL/Eyesafe DIAL	Near-IR	Mid-IR
Energy/Pulse	1.0 J	1.0 J
Pulse-Repetition Frequency	10 Hz	10 Hz
Tuning Range	0.7 - 1.0 μm	2.5 - 5.5 μm
Linewidth	1.0 pm	2.0 pm
Pulselength	< 0.3 μsec	≤ 1.0 μsec
Lead Center	LaRC	LaRC

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

In-Situ Lasers/Seed Sources	Near-IR	Mid-IR
Power	50 mW	50 mW
Linewidth	< 30 MHz	< 10 MHz
Wavelength	0.73 μm	2.09 μm
Lifetime	50,000 hrs.	50,000 hrs.
Laser Diode Materials/Pump		
Power/Area	1500 W/cm^2	1500 W/cm^2
Linewidth	0.003 μm	0.003 μm
Wavelength	0.67 μm	1.63, 1.70 μm
Lifetime	5 • 10^9 shots	5 • 10^9 shots
Lead Center	JPL	JPL

OBJECTIVE: ENHANCE LASER RELIABILITY AND PERFORMANCE

High-Energy Optics	1.06, near-IR, 2.1, mid-IR
Increase in Energy Density	2 times
Database	LaRC database
Design Standards/Testing	Establish
Qualify Vendors/Techniques	Establish
Lead Center	LaRC

OBJECTIVE: DEVELOP IMPROVED DETECTION OF LIDAR SIGNALS

Receiver Technology	1.06/0.53	2.1	Mid-IR
Type	Emissive	PV	PV
Quantum Efficiency	> 0.01/0.30	> 0.5	> 0.5
Bandwidth	1.0 GHz	1-5 GHz	5 MHz
Elements	1	1 and 3 x 3	1 and 3 x 3
Integrated Amplifier	Dynodes	Electronic	Electronic
Lead Center	GSFC	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

INSTRUMENT	BREADBOARD
Doppler Lidar	
CO_2	1994
Ho:YLF	1997
DIAL/Eyesafe Dial	
Near-IR	1993
Mid-IR	1997
Laser Ranging	1994

TECHNOLOGY PROGRAMS TIMETABLE

TECHNOLOGY	TECHNOLOGY DEMONSTRATION
In-Situ Lasers	
Near-IR	**1996**
Mid-IR	**1996**
High-Energy Optics	
1.06 μm	**1995**
Near-IR	**1996**
2.1 μm	**1997**
Mid-IR	**1997**
Receiver	
1.06/0.53	**1998/1996**
2.1 μm	**1995**
Mid-IR	**1997**
Models/Spectroscopy	
QM Model	**1994**
Laser Model	**1996**
Spectroscopy 2.1	**1995**
Diode Laser Materials	
0.67 μm	**1997**
1.7 μm	**1997**
Scanner	**1998**

FLIGHT PROGRAMS TASK AUGMENTATION 1993

Program/Task	Centers	Budget
CO_2	MSFC	650
HO:YLF	LaRC	1550
DIAL/Eyesafe DIAL		
Near-IR	LaRC	300
Mid-IR	LaRC	600
Laser Ranging	GSFC	300
	Total	3400

TECHNOLOGY DEVELOPMENT

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

SUMMARY

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

Technology Element: Laser Sensors ($K (NET)

Sub-Element Resources:	1994	1995	1996	1997	1998	1999	2000	2001
Eye-Safe Doppler Lidar	5000	5000	5000	5000	5000	5000	5000	5000
DIAL/Eye-Safe DIAL	2500	5000	5000	5000	5000	5000	5000	5000
Ranging/Altimetry	1000	1500	2000	2250	2500	2500	2500	2500
In-Situ Laser	2000	2500	2750	2750	2750	2750	2750	2750
High-Energy Optics	500	1200	1000	1000	1000	1000	1000	1000
Receiver Technology	1000	1000	1000	1000	1000	1000	1000	1000
Models/Spectroscopy	800	800	800	800	800	800	800	800
Laser Diode Materials	1000	1500	2000	2250	2250	2250	2250	2250
Scanning Lidar	700	1200	2200	2200	4000	4000	4000	4000
Sub-Element Totals:	14500	19600	21750	22250	24300	24300	24300	24300

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

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 EOS-B (2006, 2011) MULTIFREQUENCY IMAGING MICROWAVE RADIOMETER (MIMR)
  - 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) ($\Delta T = 6\mu K$)
- GALACTIC RADIO ASTRONOMY-VERY LONG BASELINE INTERFEROMETER (VLBI)
  - 25 METER RADIO TELESCOPE IN SPACE

691 0701 001 348 M

PASSIVE MICROWAVE SENSING

TECHNOLOGY CHALLENGES/APPROACH

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

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

PASSIVE MICROWAVE SENSING

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

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

PASSIVE MICROWAVE SENSING

STATE OF THE ART ASSESSMENT

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)

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

PASSIVE MICROWAVE SENSING

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

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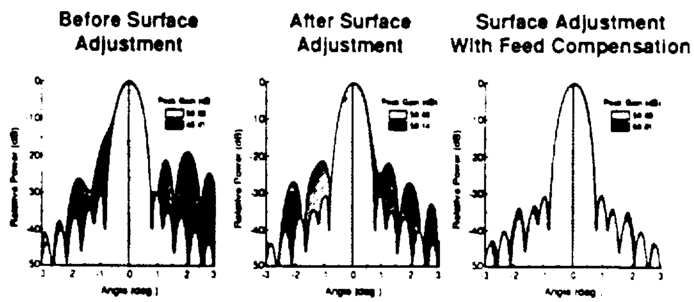
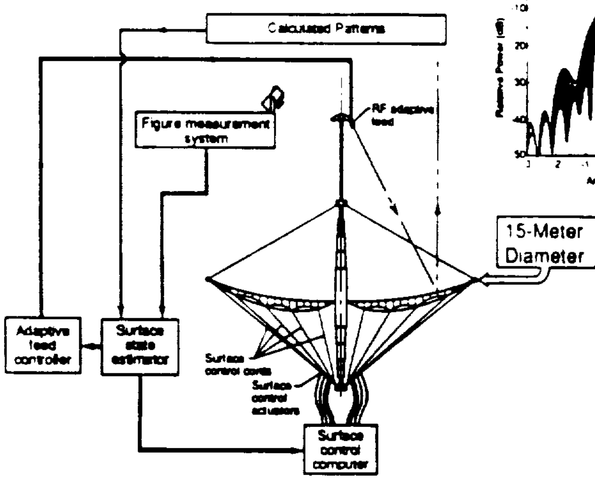
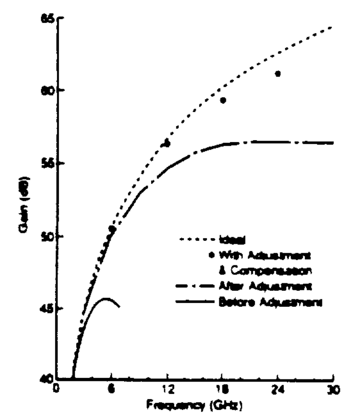
LARGE SPACE ANTENNA CAPABILITY DEMONSTRATED FOR SELF-CORRECTION IN SPACE

Calculated E-plane Radiation Patterns







SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING
PASSIVE MICROWAVE SENSING

Focused Technology Performance Objectives

Earth Science Observable	Freq. (Ghz)	Spatial Resolution (km)		Radiometric Temperature (Minimum ΔT K)
		Requirement	Goal	
Precipitation over ocean	19 37 50 - 60	1 - 30 1 - 30 1 - 30	16 8 6	1.0
Precipitation over land	37 50 - 60	1 - 30 1 - 30	8 6	1.0
Water vapor* Total	19 22 37	5 - 20 5 - 20 5 - 20	16 14 8	0.50
Profile	22 37	5 - 20 5 - 20	14 8	0.25
Temperature profile	50 - 60	5 - 30	6	0.25
Surface wind speed	19	10 - 50	16	0.50
Cloud base height	35 Active	5 - 25	N/A	N/A
Cloud water content** (Over ocean)	19 22 37	1 - 30 1 - 30 1 - 30	16 14 8	0.50
Atmospheric winds profile	37 Active	50	N/A	N/A
Snow Cover	19 37	1 - 30 1 - 30	16 8	1.0
Ocean Currents	10 - 30 Active	1 - 30	N/A	N/A

* Requires all three frequencies

** Requires two of the three frequencies

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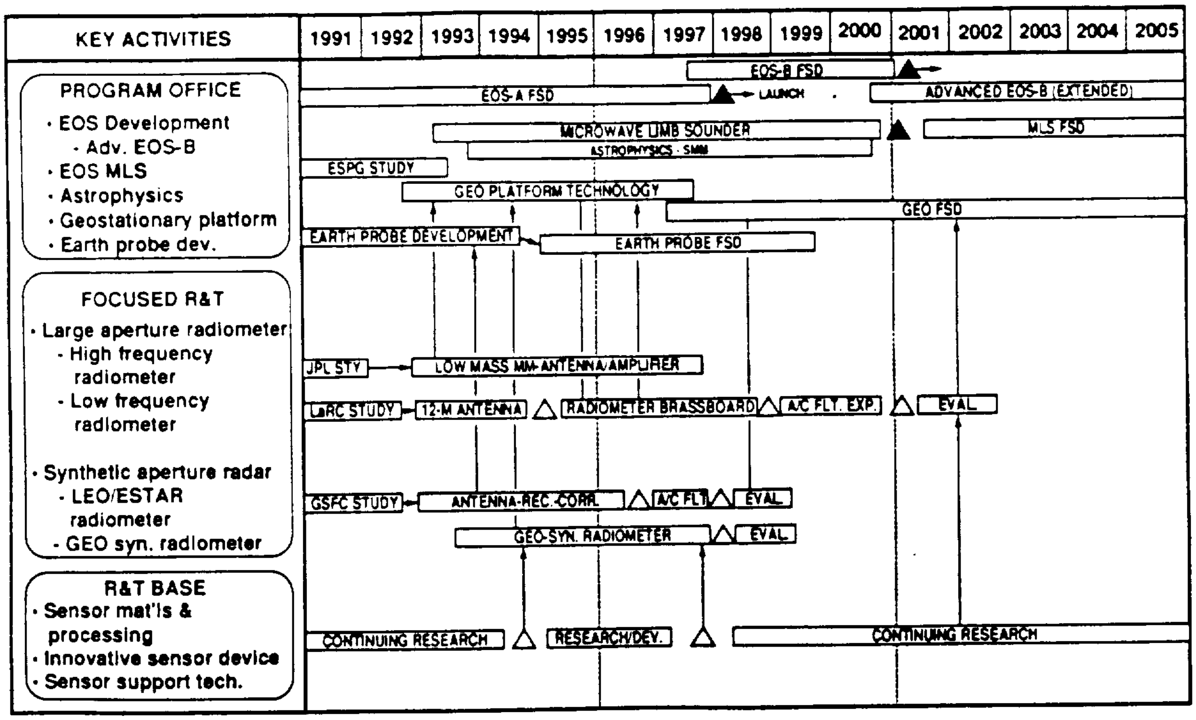
PASSIVE MICROWAVE SENSING

TECHNOLOGY ROADMAP/SCHEDULE



SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

PASSIVE MICROWAVE SENSING

OTHER DEVELOPMENT EFFORTS

- RADIOMETER MMIC DEVELOPMENT (ITT/MARTIN MARIETTA) (DARPA FUNDED MIMIC 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.

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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)

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

PASSIVE MICROWAVE SENSING

PRELIMINARY FY'93 AUGMENTATION - PRIORITIZATION

PRIORITY	ITEM	FUNDING ($M)				
		93	94	95	96	97
1	Synthetic aperture microwave radiometer	.75	1.0	2.0	2.5	2.75
	Precision membrane reflector antenna	.75	1.0	2.0	2.5	2.5
	Precision solid reflector antenna	1.0	1.5	2.5	3.0	3.75
	Phased array electronic scanning	.50	1.0	1.4	2.0	2.0
	MMIC radiometer components & amplifier	1.0	1.0	2.0	3.5	3.0
	Measurement & calibration		0.5	0.9	1.5	2.0
2	Quasi-optical millimeter components		0.5	0.5	0.5	0.2
	Acousto optical spectrometer					
3	RF rejection technology for radiometers		0.5	0.5	0.3	0.1
	Piezoelectric technology for antenna surface			0.2	0.2	0.2
	Digital correlation spectrometer					
	TOTAL (Code RC)	4.0	7.0	12.0	16.0	16.5

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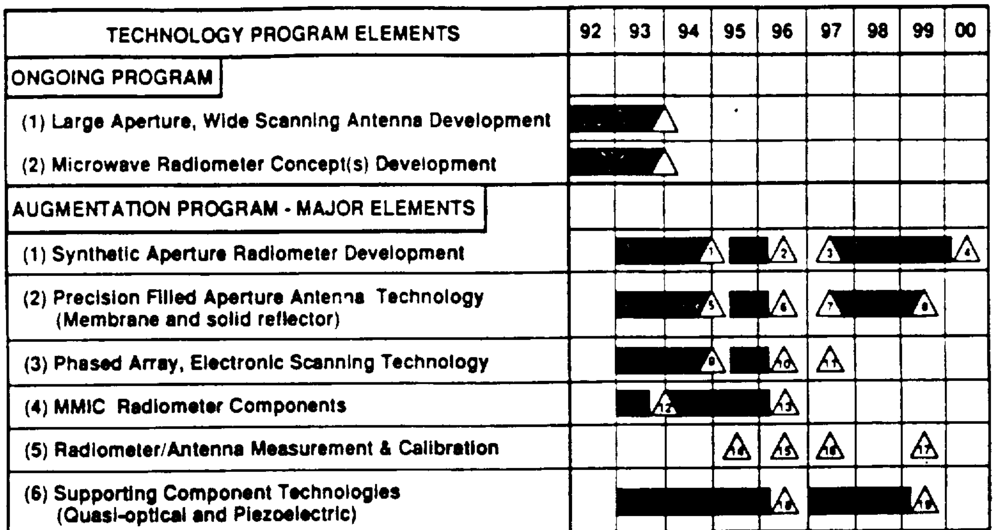
PASSIVE MICROWAVE SENSING

PROGRAM CRITICAL MILESTONES



1. Correlation-receiver designed
2. Engineering model
3. Aircraft flight test
4. Final system evaluation
5. Reflector concepts designed
6. Laboratory test beds completed
7. Near field EM tests completed
8. Final reflector performance evaluated
9. Electronic phased array dev. model delivered
10. Electronic phased-array feed integration
11. Scanning performance evaluation
12. MMIC radiometer chip design w/HEMT LNA
13. MMIC Radiometer chip delivered
14. Preliminary radiometer lab tests
15. Radiometer calibrations
16. Aircraft flight tests
17. Final radiometer performance predictions
18. Beamforming network developed
19. Final performance predictions

691 0701 001 349 M

PASSIVE MICROWAVE SENSOR TECHNOLOGY

FY'93 Obligation Plans
Estimated Funding Guideline $4.0M

Technology Research Areas - Total Program -	*Costing Method FY'93*	*Funding Amount $K*
Research Level - **University research** (Atmospheric and surface science, synthetic aperture research) - **Industry/government** (Radiometer designs)	• **University grants** (Ga. Tech., U. Mass., ODU, UVA) • **Industrial contracts** (Task existing industry assignment contracts; Martin Marietta, TRW, EMS) • **NASA in house computer aided design/ analysis**	$1,200
Device Level Technologies - **MMIC radiometers** (HEMT LNA, receiver arrays, limiters/filters) - **Beam forming devices**	• **Industry Contracts** (Existing task assignment contracts) • **DoD coordination** (WRDL, RADC, MMIC receiver tasks)	$1,350
Subsystem Level Technologies - **Phased array, wide scanning network** - **Subscale aperture/near field system** - **Radiometer measurement/calibration**	• **NASA in-house fabrication** • **Industry task assignments contract on phased array development and near field system**	$930
System Integration Technologies - **Integrated reflector system evaluation** - **Integrated radiometer system evaluation** - **Aircraft remote sensing evaluations**	• **In-house radiometer evaluation** • **Existing industry contract for near field tests** • **Coordinated flight tests** (GSFC)	$520*
	Total	$4,000

* FY'93 development contracts awarded

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

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

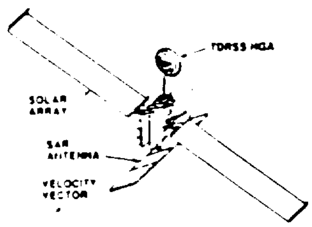
ACTIVE MICROWAVE SENSORS

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)***

JPL

EOS SAR OVERVIEW



EOS SAR

MULTI-POLARIZATION, MULTI-FREQUENCY SAR PROCESSOR

PUNTA DE CACAO, BELIZE – 3-FREQUENCY SAR IMAGE

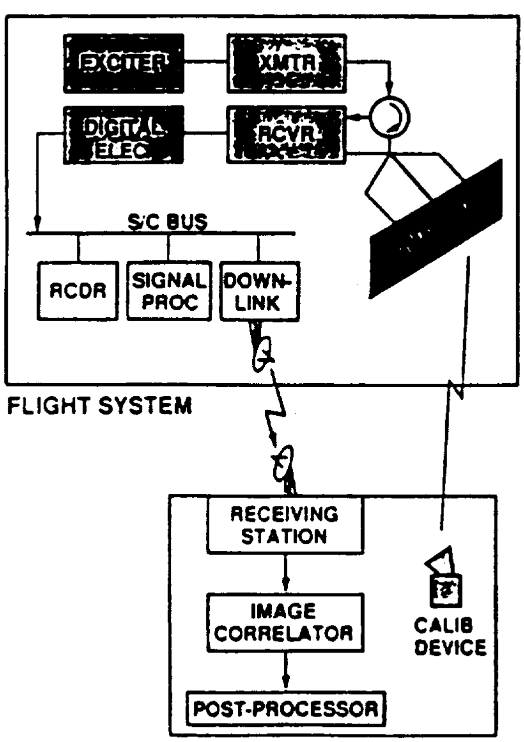
- SAR PROVIDES DIRECT MEASUREMENT OF SURFACE ROUGHNESS AND DIELECTRIC CONSTANT
- MULTIPLE SIMULTANEOUS MEASUREMENTS AT DIFFERENT POLARIZATIONS AND FREQUENCIES PROVIDE INDEPENDENT CHARACTERIZATIONS OF THE SURFACE (SUBSURFACE) PROPERTIES
  - POLARIZATION DATA CONTAINS DETAILED SCATTERING INFORMATION
- 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)

JCC-8

ADVANCED RADAR TECHNOLOGY

JPL

EOS SAR TECHNOLOGY CHALLENGES



FLIGHT SYSTEM

GROUND SYSTEM

FLIGHT SYSTEM

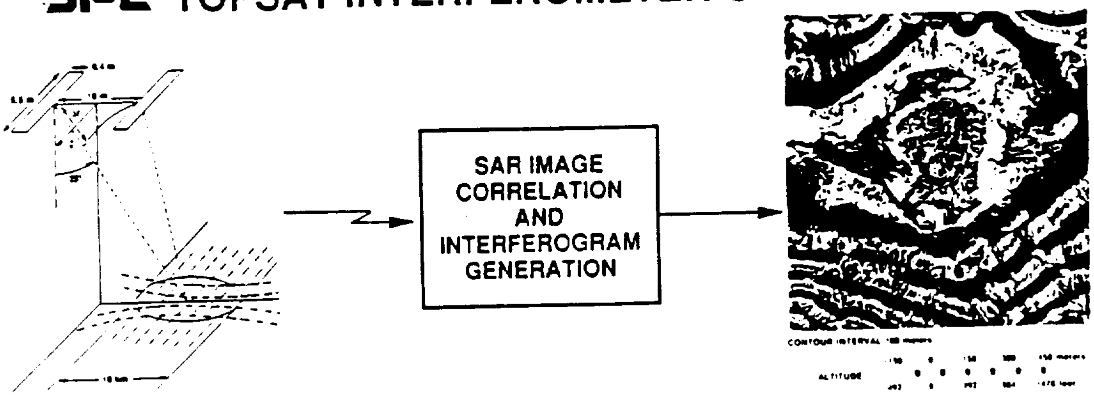
- ANTENNA (20 m x 4.5 m)
  - LIGHT WEIGHT MATERIALS (2kg/m^3) COMPACT/DEPLOYABLE STRUCTURES
    - MECHANISMS
  - CONFORMAL ARRAY DESIGNS
- RF ELECTRONICS
  - MMIC COMPONENTS
    - HIGH EFFICIENCY (50%), HIGH YIELD T/R MODULES, PHASE SHIFTERS
    - MODULE LAYOUTS, CONTROL SYSTEMS
- DIGITAL ELECTRONICS
  - 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

JCC-9

ADVANCED RADAR TECHNOLOGY
JPL TOPSAT INTERFEROMETER OVERVIEW



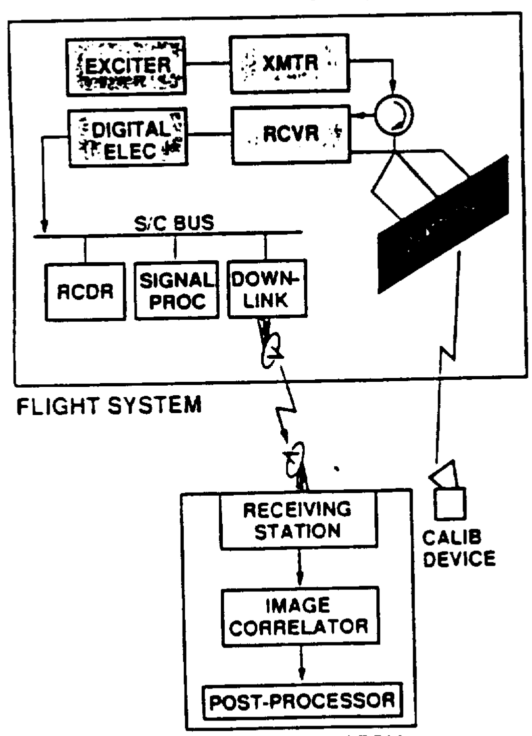
TOPSAT SENSOR

DEATH VALLEY COTTONBOWL BASIN

- 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

JCC-13

ADVANCED RADAR TECHNOLOGY
JPL TOPSAT INTERFEROMETER TECHNOLOGY CHALLENGES



FLIGHT SYSTEM

GROUND SYSTEM

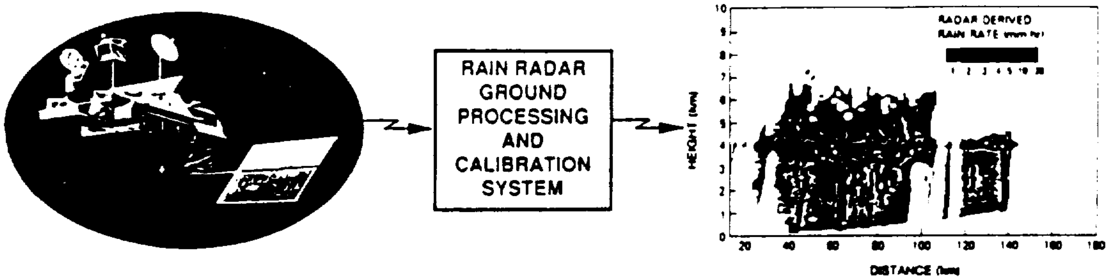
- FLIGHT SYSTEM
  - [redacted] (5.5 x 0.4 @ 35 GHz)
    - SURFACE DISTORTION COMPENSATION TECHNIQUES (ELECTRONIC, MECHANICAL)
    - LOW LOSS FEED SYSTEMS
    - ATTITUDE DETERMINATION TO 2.5 ARCSEC
  - RF ELECTRONICS
    - MMIC COMPONENTS AT 35 GHz
    - HIGH POWER (>250W), HIGH EFFICIENCY (35%) TWTs
  - DIGITAL ELECTRONICS
    - ASIC DIGITAL SYSTEMS
      - INTEGRATED EXCITERS
      - LOW POWER, COMPACT DIGITAL UNITS
    - ON-BOARD STRECH PROCESSING
- GROUND SYSTEM
  - IMAGE CORRELATOR
    - ALGORITHM DEVELOPMENT FOR BASELINE DETERMINATION (100 MICRONS @ .01s INTEG TIME)
    - ALGORITHM DEVELOPMENT FOR HIGH PHASE PRECISION COMPLEX IMAGE PRODUCTION (27 GB/ORBIT)
  - POST-PROCESSOR
    - ALGORITHMS FOR AUTOMATED IMAGE REGISTRATION, CALIBRATION, INTERFEROGRAM GENERATION AND PHASE UNWRAPPING

JCC-14

JPL

ADVANCED RADAR TECHNOLOGY

ADVANCED RAIN RADAR OVERVIEW



RAIN RADAR

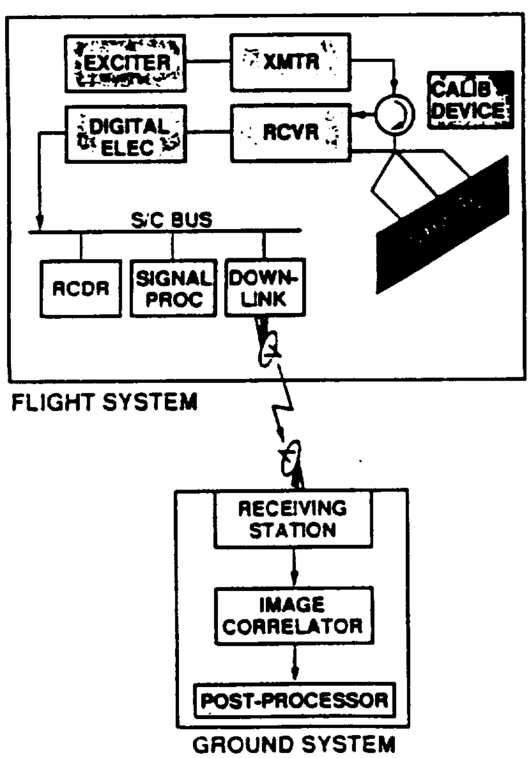
- RAIN RADAR MEASURES RETURN ECHO POWER VERSUS ECHO DELAY TIME
  - DERIVES 3-DIMENSIONAL RAINFALL MEASUREMENTS
- LOW EARTH ORBITING SYSTEM WITH ELECTRONIC BEAM SCANNING
  - PROVIDES WIDE SWATH COVERAGE AT ~ 5 km SPATIAL RESOLUTION
- GEOSTATIONARY PLATFORM
  - LONG-TERM, NEAR CONTINUOUS OBSERVATIONS
  - RAIN/CLOUD COLUMNAR HEIGHT STUDIES
- HIGH FREQUENCY RADAR DESIGNS (15-90 GHz)
  - IMPROVED SNR, RESOLUTION

JCC-18

ADVANCED RADAR TECHNOLOGY

JPL

RAIN RADAR
TECHNOLOGY CHALLENGES



- FLIGHT SYSTEM
  - [redacted] (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 TANSMITTERS (> 600W)
      - MMIC COMPONENTS (DISTR ACTIVE 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 CALIBRATATION

JCC-19

ACTIVE MICROWAVE SENSORS

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 ACIVE 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

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

ACTIVE MICROWAVE SENSORS

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 (15-60 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 (LaRC - 15M, JPL - 5M GALILEO)

RADAR TECHNOLOGY PERFORMANCE OBJECTIVES

PERFORMANCE REQUIREMENT	Current SOA SIR-C	EOS-B SAR	Topographic Radar	Rain Radar (Geostationary)
Antenna Size	12 X 4 M	16 X 4 M	2 - 5.5 X 0.4 M	10M Diameter
Frequency	1.3,5.3,9.6 GHz	1.3,5.3,9.6 GHZ	35 GHz	35,94 GHz
Antenna Structure	Aluminum	Composite	Composite	Composite
Surface Accuracy	0.5 cm	0.5 cm	0.1 cm	0.03 cm
Antenna Mass	75 kg/m^2	< 20 kg/m^2	< 5 kg/m^2	< 1 kg/m^2
Peak Power	9 kW	> 10 kW	> 0.5 kW	> 2 kW
Calibration Error	~ 2-3 dB	< 1.5 dB, 10° rms	<1 dB, 3° rms	< 0.5 dB
Approximate Need Date	-	1996	1998	1999

JPL TECHNOLOGY DEVELOPMENT FOR SPACEBORNE RADARS
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

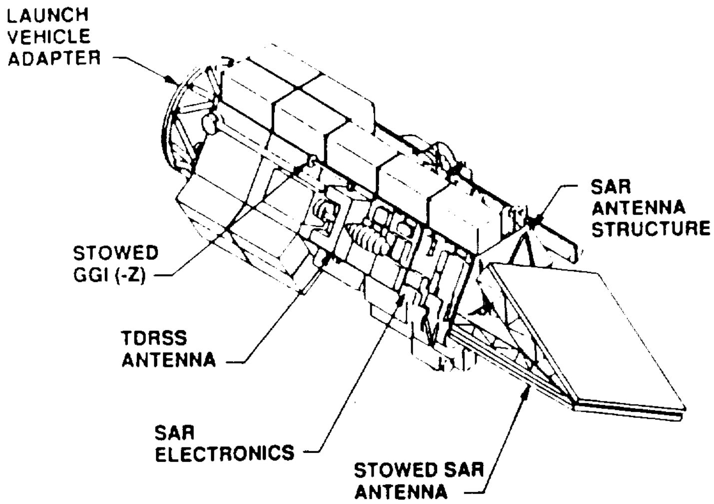
PARAMETERS	SIR-C	BASELINE Eos SAR
ANTENNA SIZE	12 x 4 m	10.9 x 2.6 m
FREQUENCY	L/C BANDS	L/C/X-BANDS
ANTENNA STRUCTURE	ALUMINUM	GRAPHITE EPOXY/HONEYCOMB
ANTENNA MASS	3283 kg	505 kg
No. T/R MODULES	252(L), 504(C)	192(L), 192(C), 384(X)
MAX PWR PER T/R MODULE	41 W(L), 10W(C)	50W(L), 15W(C), 10W(X)
ELECTRONICS WEIGHT	557 kg	330 kg
T/R MODULE TECHNOLOGY	HYBRID	HYBRID

- 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 WEGHT/POWER – SCIENCE IMPACT

* XSAR USES SINGLE TRANSMITTER/RECEIVER APPROACH, NO BEAM SCANNING

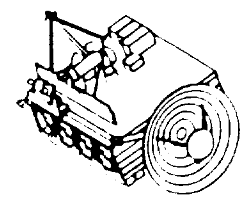
COMPARISON OF Eos-B & PRESENT BASELINE Eos SAR STOW CONFIGURATION

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

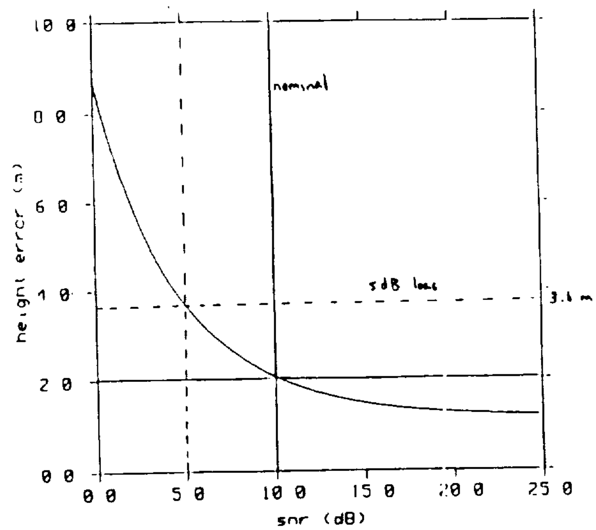
TOPSAT

Strawman System Parameters

Frequency	35 GHz
Transmit Power	250 W
Total Instrument Power	480W
Total Instrument Weight	550 kg
Pulse Length	87μsec
Bandwidth	24.2 MHz
PRF	3.88 KHz
Pulse Timing	interleave mode
Antenna Size	0.4 m × 5.5 m
Antenna Beamwidths	0.09° × 1.2°
Antenna Peak Gain	52 dB
σ_o Range	-15 to +7 dB
Transmit Loss	2.5 dB
Receive Loss	1.0 dB
Atmospheric Loss (2 way)	2.0 dB
Antenna Temperature	290 K
Receiver Noise Figure	4 dB
Dynamic Range	22 dB
Data Rate into recorder (tracking)	96 Mbps

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%



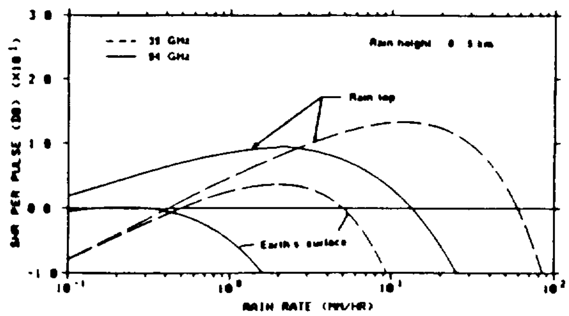
JPL

TOPSAT ATTITUDE AND ARTICULATION CONTROL
SUBSYSTEM REQUIREMENTS AND CAPABILITIES

		REQUIREMENTS
<u>ATTITUDE KNOWLEDGE ACCURACY (DEG)</u>		
	ROLL	0.0003
	YAW	0.01
	PITCH	0.01
<u>CONTROL ACCURACY (DEG)</u>		
	ROLL	0.01
	YAW	0.1
	PITCH	0.1
<u>BASELINE KNOWLEDGE ACCURACY</u>		100 microns

JPL 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); 15km (@ 94 GHz)

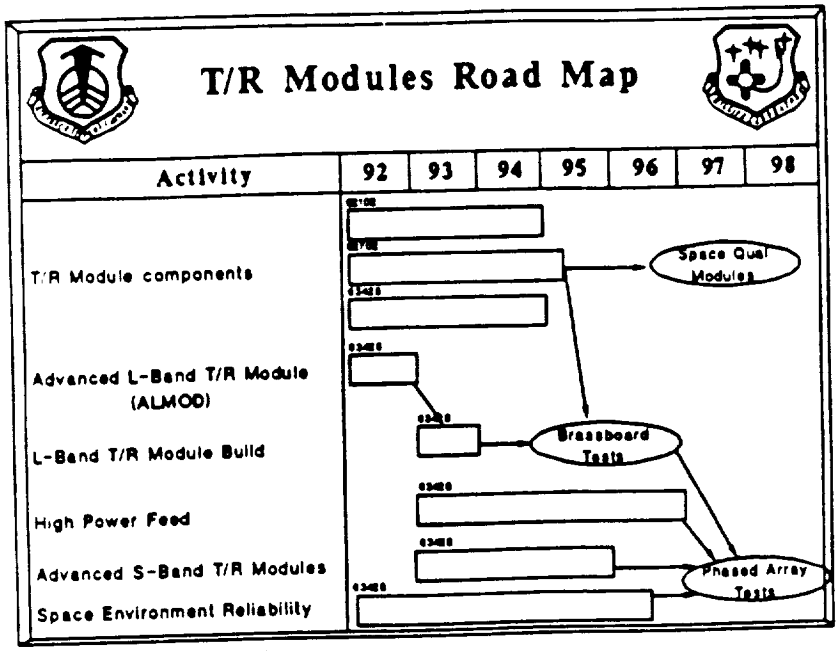


JPL TECHNOLOGY DEVELOPMENT FOR SPACEBORNE RADARS
NEAR-EARTH ORBITING CLOUD RADAR

- COMPARISON OF 35 AND 94 GHz FOR CLOUD COLUMNAR HEIGHT STUDIES:
  - CLOUD REFLECTIVITY α 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 gm^{-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

CLOUD TYPE	CLOUD THICKNESS	CLOUD WATER CONTENT (g/m^3)	SNR (dB)
STRATUS	0.5	0.2 - 0.4	+11.9
NIMBOSTRATUS	3.0	0.2 - 09	+2.6
CUMULONIMBUS	3.0	0.4 - 8.0	+5.0
CIRRIFORM (ICE)	2.0	0.02 - 0.1	+24.3

DoD "Next Generation Radar" Program



SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

ACTIVE MICROWAVE SENSORS

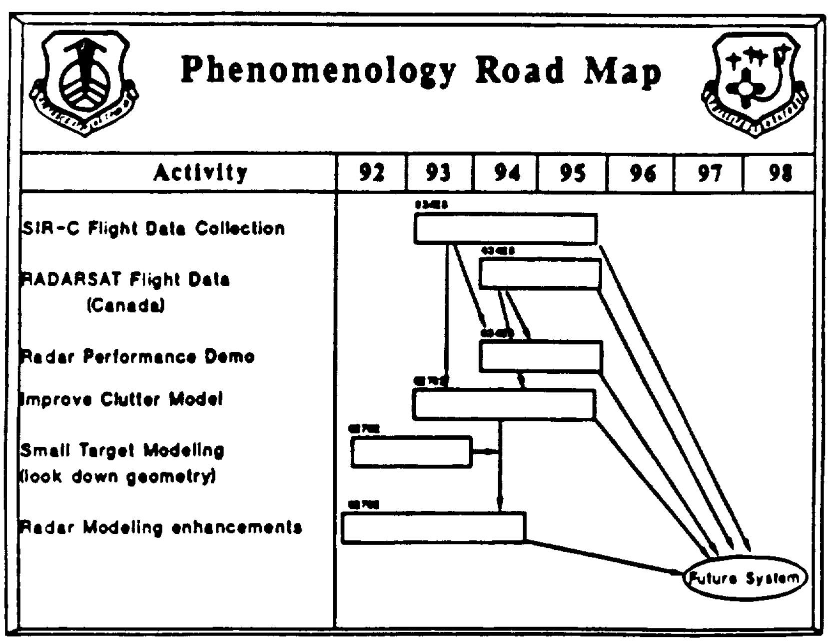
OTHER DEVELOPMENT EFFORTS

- 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
  - *EMPHSIS 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

DoD Next Generation Radar Program



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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 scansar 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, LeRC
- MISSIONS: TOPOGRAPHY MAPPER SATELLITE (TOPSAT)
- TIMEFRAME: 1993-1997
- AUGMENTED (3X) FUNDING: $3.0M (STRAGTEGIC 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 (STRAGTEGIC 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: LeRC, JPL
- MISSIONS: RAIN RADAR
- TIMEFRAME: 1994-1998
- AUGMENTED (3X) FUNDING: $0.0 (STRAGTEGIC 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 (STRAGTEGIC 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 (STRAGTEGIC 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 SCANSCAT
- TIMEFRAME: 1993-1997
- AUGMENTED (3X) FUNDING: $0.0 (STRAGTEGIC FUNDING: $4.3M)

8) OPTICALLY CONTROLLED BEAMFORMING NETWORK

- CENTERS: JPL, LeRC
- MISSIONS: TOPSAT, RAIN RADAR
- TIMEFRAME: 1993-1998
- AUGMENTED (3X) FUNDING: $0.0 (STRAGTEGIC FUNDING: $5.1M)

ACTIVE MICROWAVE SENSORS

3X PROGRAM
RESOURCE SUMMARY

CENTER: JPL, LaRC, LeRC

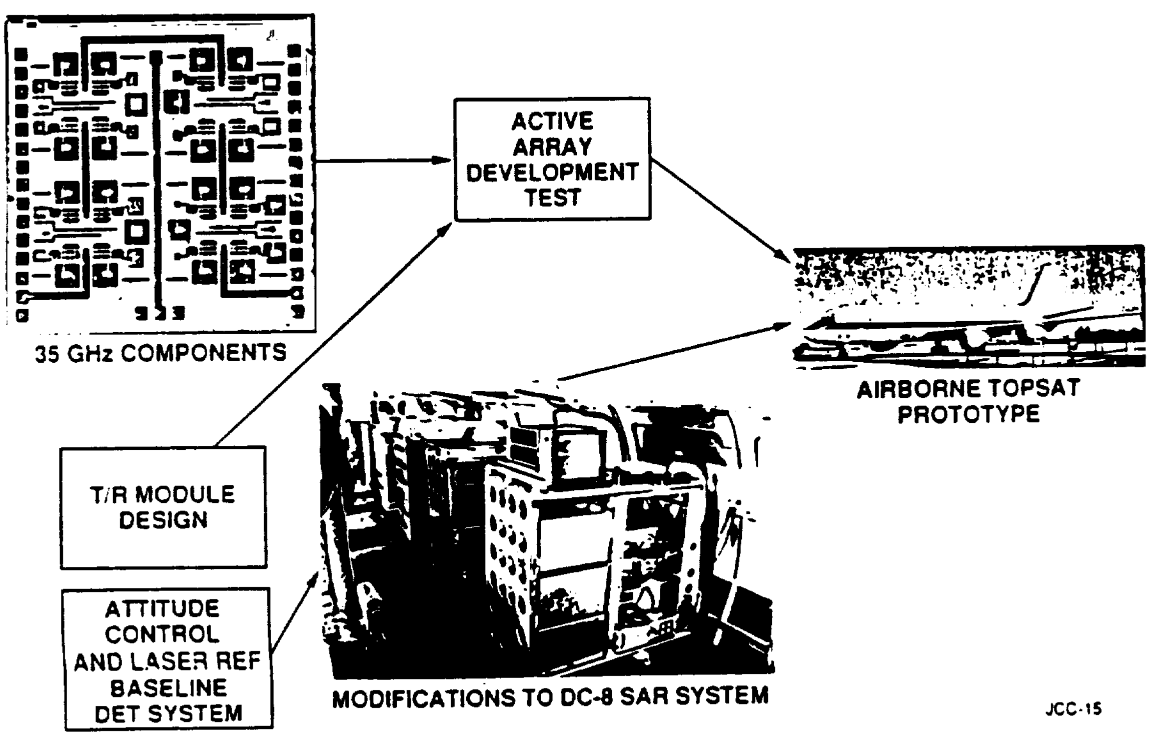
TITLE: ACTIVE MICROWAVE SENSOR TECHNOLOGY (AUGMENTATION "3X" FUNDING)

TOTAL "3X" FUNDING REQUIREMENT (CURRENT FUNDING IS $0)	FY93	FY 94	FY 95	FY 96	FY 97	TOTAL
1-10 GHz MMIC ARRAYS	0.8	1.1	1.3	0.7	-	3.9
35 GHz COMPONENTS AND ARRAY	-	-	-	0.3	2.7	3.0
CALIBRATION SUBSYSTEM	0.3	0.4	0.4	0.5	0.6	2.2
94 GHz COMPONENTS AND ARRAY	-	-	-	-	-	0.0
ASIC DIGITAL SYSTEMS	0.2	0.2	0.3	0.5	1.0	2.2
ANTENNA COMPENSATION	-	-	-	-	-	0.0
FLAT PLATE REFLECT-ARRAY	-	-	-	-	-	0.0
OPTICALLY CONTROLLED BFN	-	-	-	-	-	0.0
TOTAL	1.3	1.7	2.0	2.0	4.3	11.3

ADVANCED RADAR TECHNOLOGY

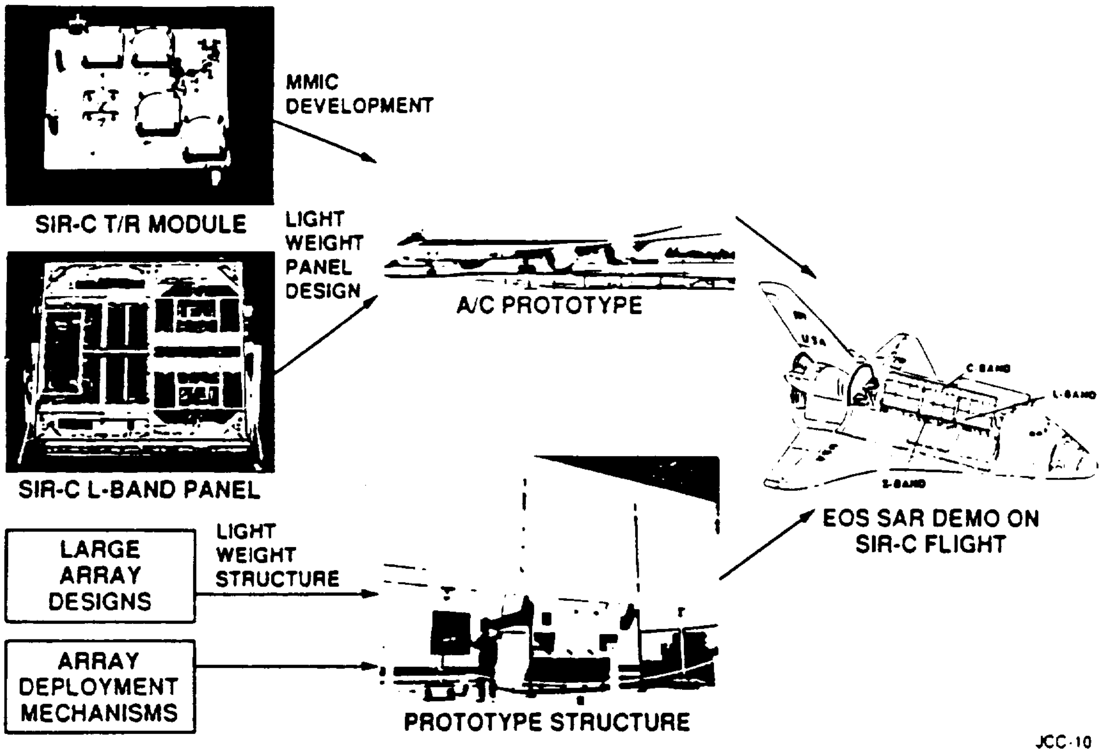
JPL

TOPSAT SENSOR A/C PROTOTYPE DEVELOPMENT



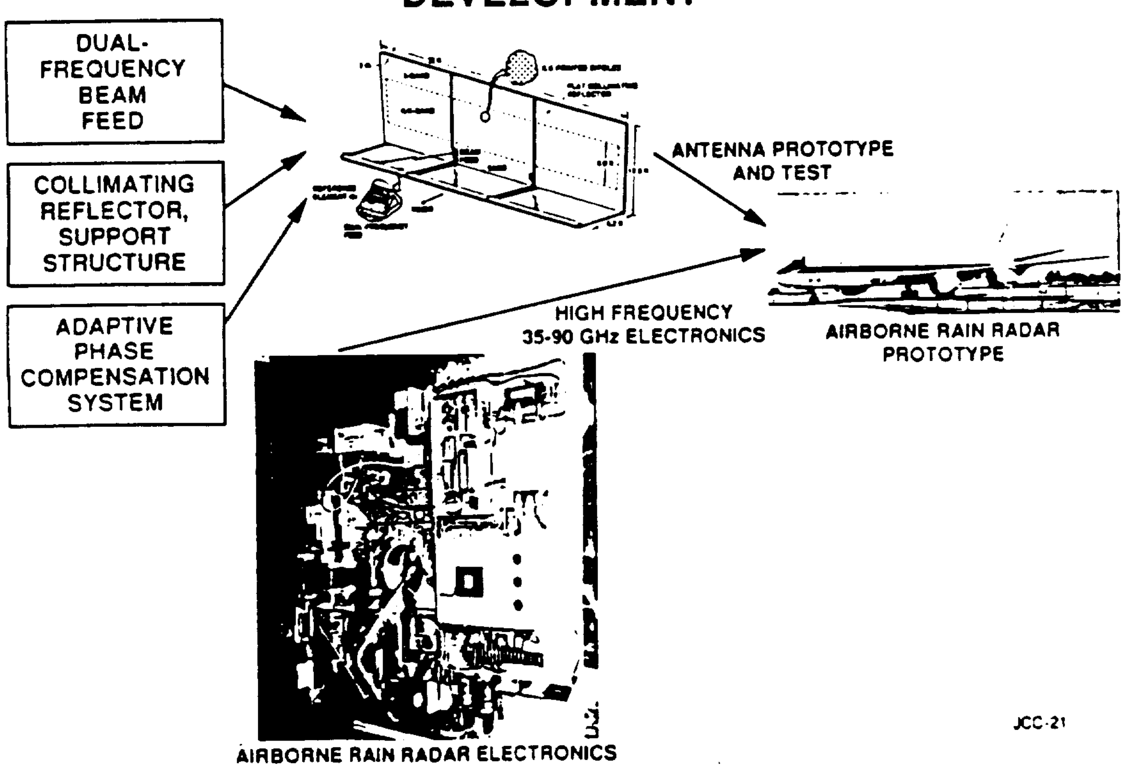
ADVANCED RADAR TECHNOLOGY

JPL EOS SAR ANTENNA TECHNOLOGY



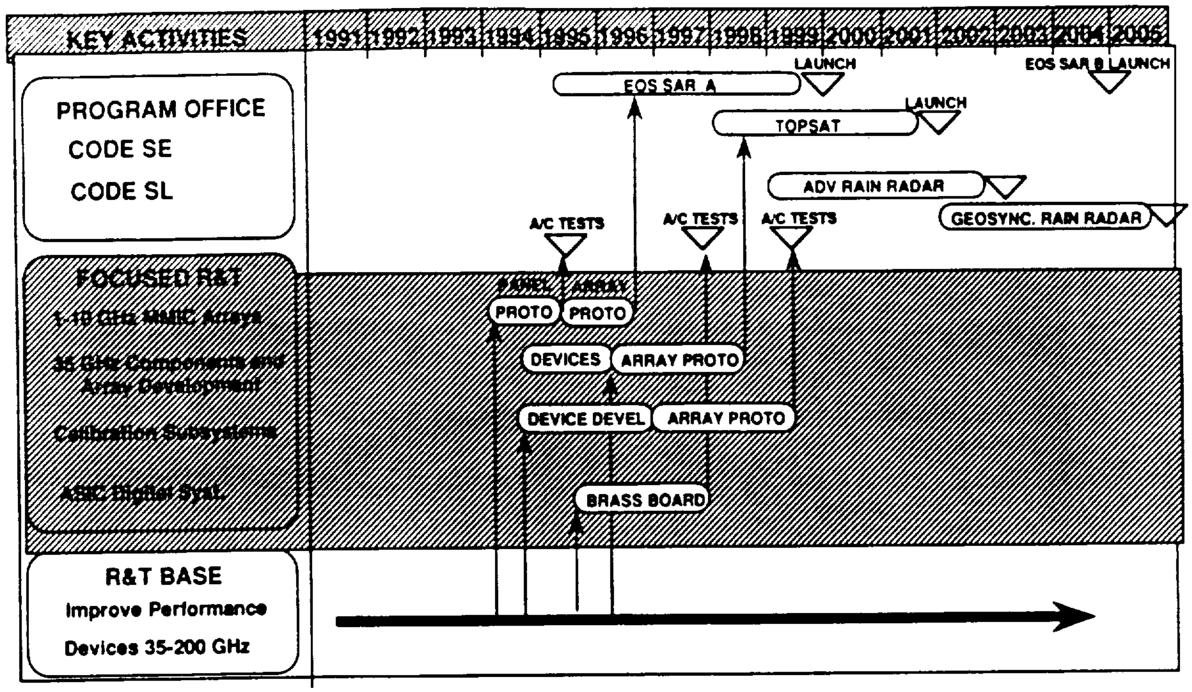
ADVANCED RADAR TECHNOLOGY

JPL RAIN RADAR ANTENNA PROTOTYPE DEVELOPMENT



ACTIVE MICROWAVE SENSORS

TECHNOLOGY ROADMAP/SCHEDULE



ACTIVE MICROWAVE SENSORS
STRATEGIC PROGRAM RESOURCE SUMMARY

CENTER: JPL, LaRC, LeRC

TITLE: ACTIVE MICROWAVE SENSOR TECHNOLOGY (STRATEGIC FUNDING)

($ K)

TOTAL FUNDING REQUIREMENT	FY93	FY 94	FY 95	FY 96	FY 97	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

		Date:	June 26, 1991
Technology Program:		LRP Thrust:	Science
Technology Area:	Science Sensors	LRP Specific Objective:	EOS Senor Technology
Technology Element:	Active Microwave Sensors	Mission Applicibility:	EOS SAR
Technology Sub-Element:	1-10 GHz MMIC Arrays		
Input Field Center:	JPL		
Input Type:	Augmentation		
Point of Contact:	John Curlander		

(FY in $M)	'93	'94	'95	'96	'97
Resource Requirements:	0.8	1.1	1.3	0.7	0.0

C of F: None

Keywords: SAR, Active Array, Microwave Sensors, MMIC

Technology Element Objectives/Description:

Demonstate feasibility of developing 20m distributed active array; three frequency: L-, C-bands quad-polarized, with peak power of 3-5 kW in each frequency band; bandwidth required >50MHz; electronic beam scanning of +/- 30 deg; polarization purity of 30dB. Use of composite structural materials to achieve mass of <20 kg/m/m and a surface accuracy of <0.5 cm peak-to-peak deflection.

Task Schedule/Milestones:

FY93: T/R Module evaluation and procurement; antenna stucture materials requirements analysis
FY94: Single panel prototype development; and laboratory tests; array stucture design
FY95: Array prototype development; laboratory /field tests
FY96: Interface with NASA DC-8 and airborne SAR; airborne flight tests

Comments/Issues:

Adaptive phase control implementation; controller interfaces; distributed control feasibility
Array operating efficiency; tapered beam illumintion performance; phase/amplitude errors
Recommend funding be augmented to develop flight weight brassboard panel and control system

		Date:	June 26, 1991
Technology Program:		LRP Thrust:	Science
Technology Area:	Science Sensors	LRP Specific Objective:	EOS Sensor Technology
Technology Element:	Active Microwave Sensors	Mission Applicibility:	EOS SAR
Technology Sub-Element:	35 GHz Components/Array		
Input Field Center:	JPL, LeRC		
Input Type:	Augmentation		
Point of Contact:	John Curlander		

(FY in $M)	'93	'94	'95	'96	'97
Resource Requirements:	2.0	3.0	3.0	2.6	1.7

C of F: None

Keywords: Topograghic mapper system, SAR, Microwave Sensors,

Technology Element Objectives/Description:

Demonstate feasibility of developing >5m distributed active array or passive array at Ka-band; peak power of >600W ; bandwidth required >50MHz; high phase precision/stability across multiple antennas <5 deg rms; polarization purity of 30dB. Use of composite structural materials to achieve mass of <5 kg/m/m and a surface accuracy of <0.1 cm peak-to-peak deflection.

Task Schedule/Milestones:

FY93: MMIC T/R Module evaluation; TWT evaluation; procurement of test articles; laboratory tests
FY94: Breadboard prototype development; and laboratory tests; array stucture design
FY95: Ka band radar RF and digital subsystems development
FY96: Array prototype development; laboratory /field tests
FY97 Interface with NASA DC-8 and airborne SAR; airborne flight tests

Comments/Issues:

Array flatness, adaptive phase control implementation; controller interfaces; distributed control
System operating efficiency; pointing determination accuracy; phase/amplitude errors

		Date:	June 26, 1991
Technology Program:		LRP Thrust:	Science
Technology Area:	Science Sensors	LRP Specific Objective:	EOS Sensor Technology
Technology Element:	Active Microwave Sensors	Mission Applicibility:	EOS SAR, TOPSAT
Technology Sub-Element:	Calibration Subsystems		
Input Field Center:	JPL		
Input Type:	Augmentation		
Point of Contact:	John Curlander		

(FY in $M)	'93	'94	'95	'96	'97
Resource Requirements:	0.3	0.4	0.4	0.5	0.6

C of F: None

Keywords: Radiometric calibration, SAR, Microwave Sensors, Global Positioning System

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 electronis 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

		Date:	June 26, 1991
Technology Program:		LRP Thrust:	Science
Technology Area:	Science Sensors	LRP Specific Objective:	EOS Sensor Technology
Technology Element:	Active Microwave Sensors	Mission Applicibility:	EOS SAR, TOPSAT
Technology Sub-Element:	ASIC Digital Subsystems		
Input Field Center:	JPL		
Input Type:	Augmentation		
Point of Contact:	John Curlander		

(FY in $M)	'93	'94	'95	'96	'97
Resource Requirements:	0.2	0.2	0.3	0.5	1.0

C of F: None

Keywords: ASIC SAR, Microwave Sensors, Digital Electronics

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 6bps, 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 subsytems 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 substantiall reduced with on-board signal processing and multi-lookfiltering; large cost savings in ground data handling, more efficient data distribution.

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

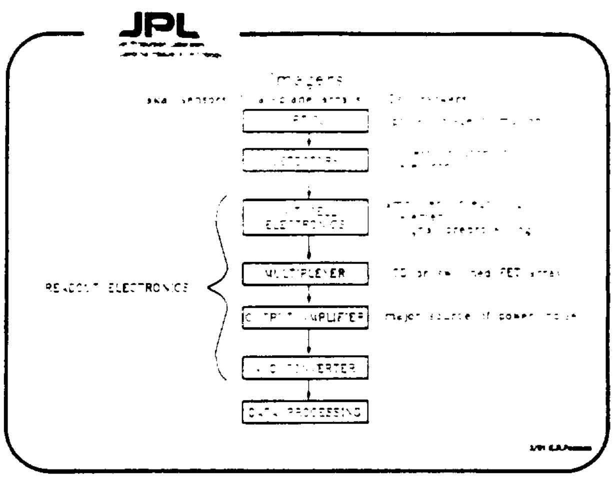
SENSOR ELECTRONICS PROJECT SUMMARY

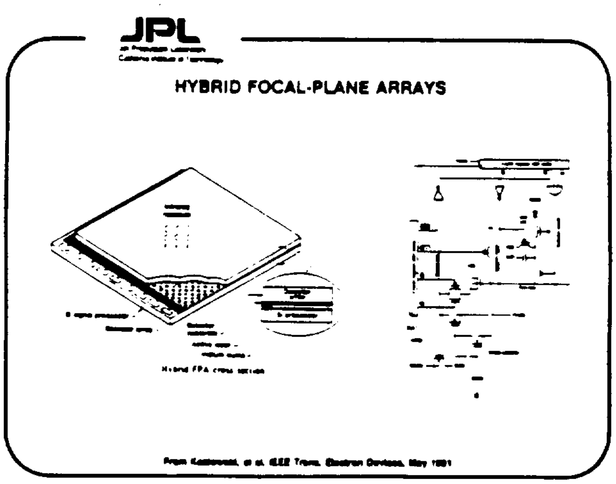
SCIENCE SENSING PROGRAM AREA OF THE SPACE SCIENCE TECHNOLOGY PROGRAM

June 27, 1991

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

Washington, D C. 20546





JPL

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 applcblty, less $

JPL

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 real-estate.

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SENSOR ELECTRONICS

TECHNOLOGY NEEDS

- SENSOR ELECTRONICS ADDRESSES THE NEEDS FOR DETECTOR READOUT AND PACKAGING INCLUDING AMPLIFIERS, MULTIPLEXERS, BACKPLANE PROCESSING, AND DATA CONVERSION

- CURRENT TECHNOLOGY CANNOT MEET REQUIREMENTS FOR FUTURE MISSIONS IN THE UV, VIS, IR, X-RAY, AND γ-RAY REGIMES - HST, SIRTF, LDR, MOI, LTT NAE, GRBO, FUSE, AXAF, XST, HXIF, VHTF, SAFIRE, SAGE III, LITE II, SALSA, SMILS, ESTAR, NGST, MLS II, 8 etc. WHICH INCLUDE:
  - CRYOGENIC OPERATION
  - SUB-ELECTRON NOISE
  - HIGH THROUGHPUT
  - LOW POWER CONSUMPTION

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SENSOR ELECTRONICS

TECHNOLOGY CHALLENGES/APPROACH

- CRYOGENIC READOUT ELECTRONICS OPERATING IN THE 2-4K RANGE
  - 2 DEG FETs, SI CMOS, JFETS, SUPERCONDUCTORS
- SUB-ELECTRON READ NOISE IN CCDS AND IR SWITCH ARRAY MUXs
  - HIGH SENSITIVITY OUTPUT AMPLIFIER
  - ADVANCED CMOS CIRCUITS
- INCREASED ELECTRONICS INTEGRATION WITH REDUCED HEAT LOAD AND LOWER NOISE
  - 3D MICROELECTRONICS (SOI, Z-PLANE, e-SI)
  - ADVANCED INTERFACES (OPTICAL LINKS)
  - LARGE FORMAT ARRAYS/MOSAICS
- INCREASED SENSOR SYSTEM THROUGHPUT
  - ADVANCED ARCHITECTURES FOR SMART READOUT
  - LOW POWER VHSIC

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING
SENSOR ELECTRONICS

STATE OF THE ART ASSESSMENT

- CRYOGENIC READOUT ELECTRONICS
  - NOISE UNACCEPTABLE BELOW 10 K
  - 1/f NOISE AT 65-80 K EXCESSIVE
- READ NOISE
  - APROX 3-5 e^- RMS IN CCDs
  - APPROX 30 e^- RMS IN IR SWITCHED ARRAY MUXs
- DETECTOR AND ELECTRONICS INTEGRATION
  - 2048 X 2048 VIS. CCD ARRAYS
  - 256 X 256 IR FPAs
  - DISCRETE CRYOGENIC READOUT ELECTRONICS
- SENSOR SYSTEM THROUGHPUT
  - CCD READOUT RATE 50 kPts

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING
SENSOR ELECTRONICS

CURRENT PROGRAM

NONE

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING
SENSOR ELECTRONICS

3X AUGMENTED PROGRAM

1) **Low-noise cryogenic readout electronics**
   Explore switch array readout technologies for low-noise cryogenic operation. No acceptable technologies have been demonstrated at 2-4 K. Significant 1/f noise remains in readout devices operating in the 60-80 K range. Approach includes 2DEGFETs, LTS, Si CMOS, JFETS.
2) **Devices and circuits for sub-electron read noise**
   Reduce read noise in CCD output amplifiers from 3-5 e^- rms to sub-electron levels. Reduce read noise in IR switch array readout mux's from 30 e^- rms to 1 e^- rms or less.
3) **Advanced packaging and interfaces**
   Develop advanced packaging and interface techniques to enhance sensor system performance. Develop packaging and readout for large mosaic CCD and IR focal-plane arrays. Develop advanced interfaces for reducing dewar heat load and noise. Explore 3-D microelectronics to increase pixel circuitry. Enhance discrete detector systems.
4) **Advanced readout architectures**
   Investigate advanced readout architectures to enhance sensor system throughput. Explore data driven readout and unit cell quantization to provide spatial and energy resolution. Microchannel plate readout system enhancement. VLSI/ULSI circuit design for micropower levels and gamma circumvention.
5) **Low power, very high speed integrated circuitry**
   Reduce power consumption by twenty-fold in microwave sensor backend electronics to allow massive on-board signal correlation and reduce data transmission rates from the spacecraft while preserving essential scientific data return. Approach includes 2DEGFETs, LTS, and Si HBT/CMOS.

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING
SENSOR ELECTRONICS

TECHNOLOGY PERFORMANCE OBJECTIVES

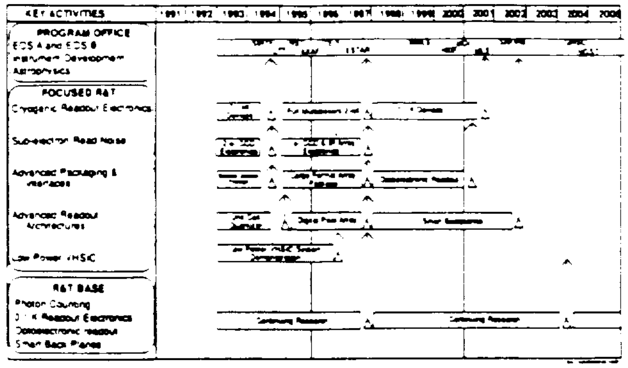
PERFORMANCE REQUIREMENT	CURRENT SOA	TYPICAL REQUIREMENT
LOW TEMPERATURE OPERATION (SIRTF, NGIR___)	15K USING SI CMOS	2-4K
LOW READ NOISE (HST, LTT, NGST___)	3-5 e^- RMS IN CCDS 30 e^- RMS IN IR SWITCHED ARRAY MUXES	1 e^- RMS
LARGE ARRAY SIZE (NGST, NGIR___)	256 X 256 (IR) (2048 X 2048) (CCD)	10^4 X 10^4
HIGH THROUGHPUT (VHTF, NGST, NGIR)	0.01 FPS (CCD)	>100 FPS
LOW POWER VHSIC (ESTAR, MLSR, SALSA	10 fJ (2DEGFET)	0.5fJ
ARRAY BUTTABILITY (NGST, NGIR___)	3 SIDES	4 SIDES

6/19/91 Page 7

SPACE SCIENCE TECHNOLOGY SCIENCE SENSING

SENSOR ELECTRONICS

TECHNOLOGY ROADMAP SCHEDULE



SPACE SCIENCE TECHNOLOGY SCIENCE SENSING

SENSOR ELECTRONICS

OTHER DEVELOPMENT EFFORTS

SDIO: SUPERCONDUCTOR FOCAL PLANE ELECTRONICS
(TRW, WESTINGHOUSE, HYPRES)

SDIO 3-D MICROELECTRONICS (Z-PLANE)
(IRVINE SYSTEMS, GRUMMAN)

DARPA MICROPOWER CMOS VLSI
(JPL)

NSF FOCAL-PLANE IMAGE PROCESSING
(COLUMBIA UNIVERSITY, MIT)

LIKELY SEVERAL OTHER CLASSIFIED PROGRAMS IN EXISTENCE

SPACE SCIENCE TECHNOLOGY SCIENCE SENSING

SENSOR ELECTRONICS

PRELIMINARY FY93 3X AUGMENTATION PRIORITIZATION

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

SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SENSOR ELECTRONICS

PROGRAM OVERVIEW

OBJECTIVES

- **Programmatic**
  Improve sensor system performance using advanced detector readout electronics and packaging technology
- **Technical**
  Cryogenic readout electronics
  Sub-electron read noise
  Advanced packaging and interfaces
  Advanced readout architectures
  Low power VHSIC

SCHEDULE

- 1993
- 1994 See breakdown of elements
- 1995
- 1996
- 1997

RESOURCES

- 1993 $1500 K
- 1994 $2700 K
- 1995 $3400 K
- 1996 $4100 K
- 1997 $6000 K

PARTICIPANTS

JPL
ARC
GSFC
LaRC

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SENSOR ELECTRONICS

BREAKDOWN (1 OF 5)
CRYOGENIC READOUT

OBJECTIVES

- Programmatic
  Low noise cryogenic electronic devices for IR focal plane array readout
  SIRTF NAE NGOVLBI NGST NGIR LDR
- Technical
  Low noise devices and readout circuits operating at 2-4 K
  Low 1/f noise devices at 60-80K

SCHEDULE

- 1993 n/a
- 1994 Devices operating at 2-4 K
- 1995 Simple circuits at 2-4 K
- 1996 Small multiplexer at 2-4 K
- 1997 Full multiplexer at 2-4 K

RESOURCES

- 1993 $ 600 K
- 1994 $ 700 K
- 1995 $ 800 K
- 1996 $ 800 K
- 1997 $1000 K

PARTICIPANTS

JPL
ARC
GSFC

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SENSOR ELECTRONICS

BREAKDOWN (2 OF 5)
SUB-ELECTRON READ NOISE

OBJECTIVES

- Programmatic
  Devices and circuits for sub-electron read noise in detector arrays
  (LTT, HST2, AXAF, HXIF, MOI, VHTF, GRSO, NGST, II)
- Technical
  Achieve <= 1 e rms read noise in CCD output amplifiers and switched array IR multiplexers

SCHEDULE

- 1993 n/a
- 1994 10 e read noise in IR switched arrays
  2 e read noise in CCDs
- 1995 5 e read noise in IR switched arrays
- 1996 2 e rms read noise in IR switched arrays
  1 e rms read noise in IR switched arrays
- 1997 sub-electron read noise in CCDs

RESOURCES

- 1993 $ 500 K
- 1994 $ 700 K
- 1995 $ 800 K
- 1996 $ 900 K
- 1997 $1000 K

PARTICIPANTS

JPL
GSFC
ARC
LaRC

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SENSOR ELECTRONICS

BREAKDOWN (3 OF 5)
ADV. PACKAGING AND INTERFACES

OBJECTIVES

- Programmatic
  Develop advanced packaging and interface techniques to enhance sensor system performance (LTT, MOI, NGST, II, XST, HXIF, VHTF, SAFIRE, LTE II)
- Technical
  Mosaic array packaging technology. Develop very large >2048x2048 CCD arrays and >256x256 IR FPAS. Develop advanced interfaces for reducing dewar heat load and noise. Develop 3-D microelectronics to increase pixel circuitry. Enhance discrete detector systems

SCHEDULE

- 1993 Investigate a-Si technology for SOI
- 1994 Low noise discrete detector packaging
- 1995 Readout technology for mosaic CCDs
- 1996 Prototype analog optical link
- 1997 Large format mosaic packaging

RESOURCES

- 1993 $ 100 K
- 1994 $ 800 K
- 1995 $1100 K
- 1996 $1400 K
- 1997 $1500 K

PARTICIPANTS

LaRC
JPL
ARC
GSFC

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SPACE SCIENCE TECHNOLOGY: SCIENCE SENSING

SENSOR ELECTRONICS

BREAKDOWN (4 OF 5)
ADVANCED ARCHITECTURES

OBJECTIVES

- Programmatic
  Investigate advanced readout architectures to increase sensor system throughput
  (VHTF, XST, AXAF, NGST, II, NGIR)
- Technical
  Explore data-driven readout and unit cell quantization. MCP readout system enhancement. Gamma circumvention.

SCHEDULE

- 1993 n/a
- 1994 Event-driven trigger circuit
- 1995 Unit cell quantizer circuit
- 1996 Demonstrate content-addressable readout
- 1997 Small array of digital pixels

RESOURCES

- 1993 $ 250 K
- 1994 $ 400 K
- 1995 $ 500 K
- 1996 $ 700 K
- 1997 $1300 K

PARTICIPANTS

JPL
Universities (Idaho, Stanford)

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SPACE SCIENCE TECHNOLOGY SCIENCE SENSING

SENSOR ELECTRONICS

BREAKDOWN (5 OF 5)
LOW POWER VHSIC

OBJECTIVES

- **Programmatic**
  Low power very high speed integrated circuits for backend microwave radiometer signal processor
  ESTAR SMILS MLS LDR SALSA
- **Technical**
  Reduce power consumption by 20 fold or more in back-end digital correlator processing circuitry

SCHEDULE

- **1993** Current technology survey 2DEGFETS Superconductors Si-HBT Si CMOS
- **1994** Downselect to 2 technologies to design proof of concept circuitry
- **1995** Downselect to 1 technology for detailed design
- **1996** System integration for a working system
- **1997** Technology utilization and transfer to various NASA programs

RESOURCES

- **1993** $ 50 K
- **1994** $ 100 K
- **1995** $ 200 K
- **1996** $ 300 K
- **1997** $1000 K

PARTICIPANTS

JPL

SPACE SCIENCE TECHNOLOGY SCIENCE SENSING

SENSOR ELECTRONICS

3X AUGMENTATION FUNDING

(No on-going work)

SUB-ELEMENT	1993	1994	1995	1996	1997	Total
1 Cryogenic readout electronics	0 60	0 7	0 8	0 8	1 0	3 90
2 Sub-electron read noise	0 50	0 7	0 8	0 9	1 0	3 90
3 Advanced packaging & interface	0 10	0 8	1 1	1 4	1 7	5 10
4 Advanced readout architectures	0.25	0 4	0 5	0 7	1 3	3 15
5 Low power VHSIC	0 05	0 1	0 2	0 3	1 0	1 65
Augmentation Total ($M)	1 50	2 7	3 4	4 1	6 0	17 70

SPACE SCIENCE TECHNOLOGY SCIENCE SENSING

SENSOR ELECTRONICS

FY '93 ALLOCATION OF 3X FUNDING

Cryogenic Readout Electronics

200 ARC Cryo CMOS
250 JPL design test and analysis of III-V circuits
150 Contract for fabrication of III-V circuits
600

Sub-electron Read Noise

100 x 5 Study contracts
500

Advanced Packaging & Interface

100 LARC Study contracts

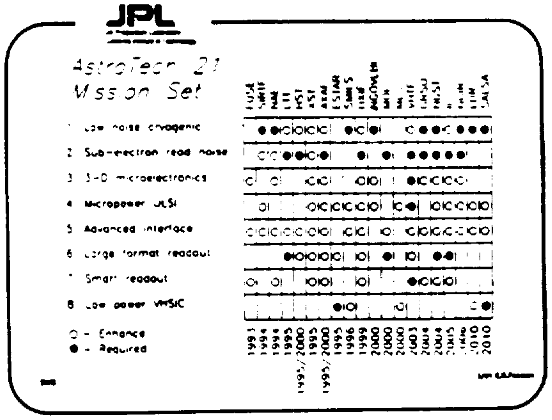
Advanced Readout Architectures

75 JPL design test and analysis
75 Contract for fabrication
50x2 University contracts
250

Low Power VHSIC

50 JPL survey needs and capabilities

JPL

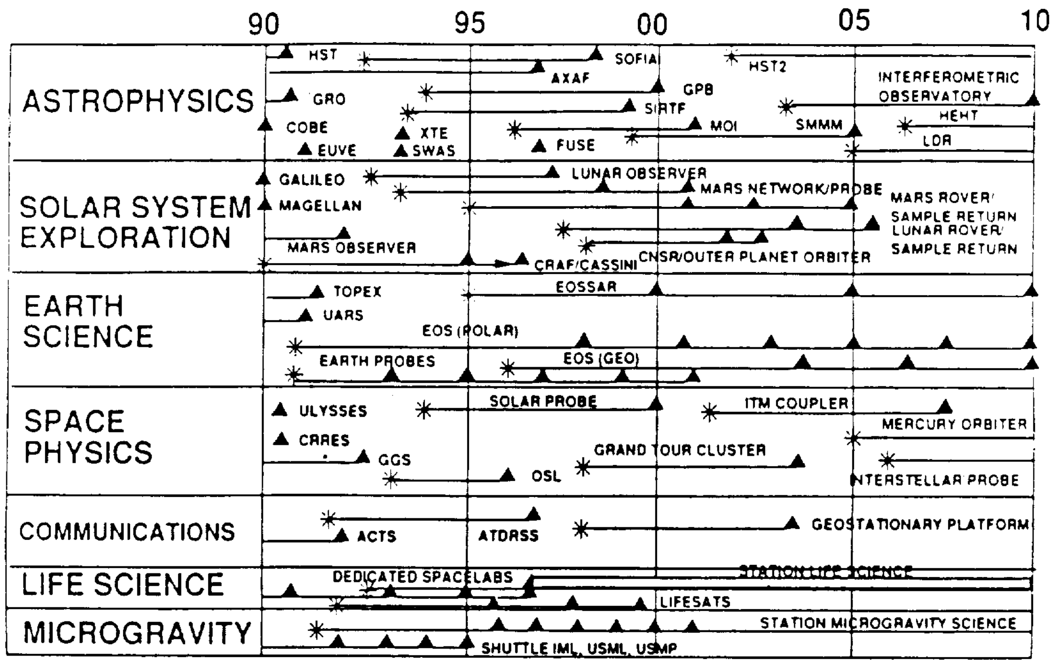


INTEGRATED SPACE TECHNOLOGY PLAN

SCIENCE

SCIENCE TECHNOLOGY MISSION MODEL

OAET



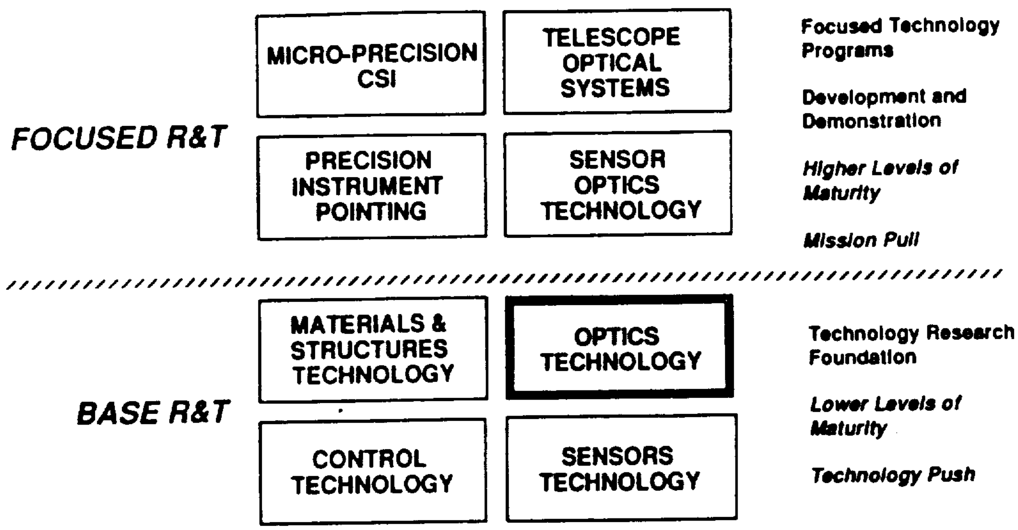
OPTICS TECHNOLOGY BASE R&T PROGRAM

OAET, OSSA AND SCIENCE COMMUNITY INPUTS TO PROGRAM PLAN

- Exploration Technology Program Plan: Lunar and Mars Science Technology Summary, November 16, 1990
- 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
- Towards Other Planetary Systems (TOPS) Technology Needs Identification Workshop, April 22-24, 1991
- Technologies for Advanced Planetary Instruments Workshop, May 8-10, 1991

OPTICS TECHNOLOGY BASE R&T PROGRAM

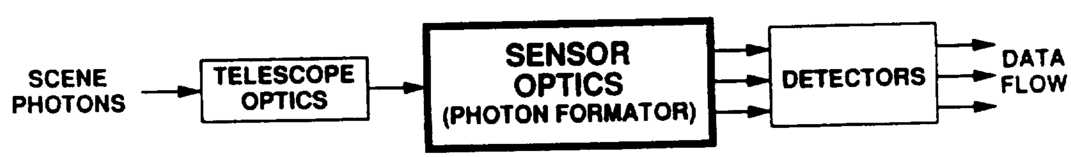
RELATIONSHIPS BETWEEN OAET PROGRAMS



SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

SENSOR OPTICAL SYSTEMS

WHERE IS IT?



SENSOR OPTICAL SYSTEMS

DEFINITION

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 accomodate sensor architecture

CHARACTERISTICS

- Smaller than telescope optics
- Sophisticated functions requiring highest quality optics
- Novel fabrication methodologies

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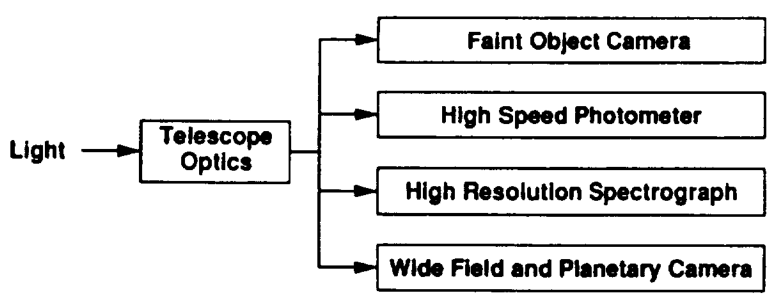
SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

SENSOR OPTICAL SYSTEMS

Criticality of SENSOR OPTICS

Example: Hubble Space Telescope



Wide Field and Planetary Camera (WF/PC)

- Re-format image to accomodate 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

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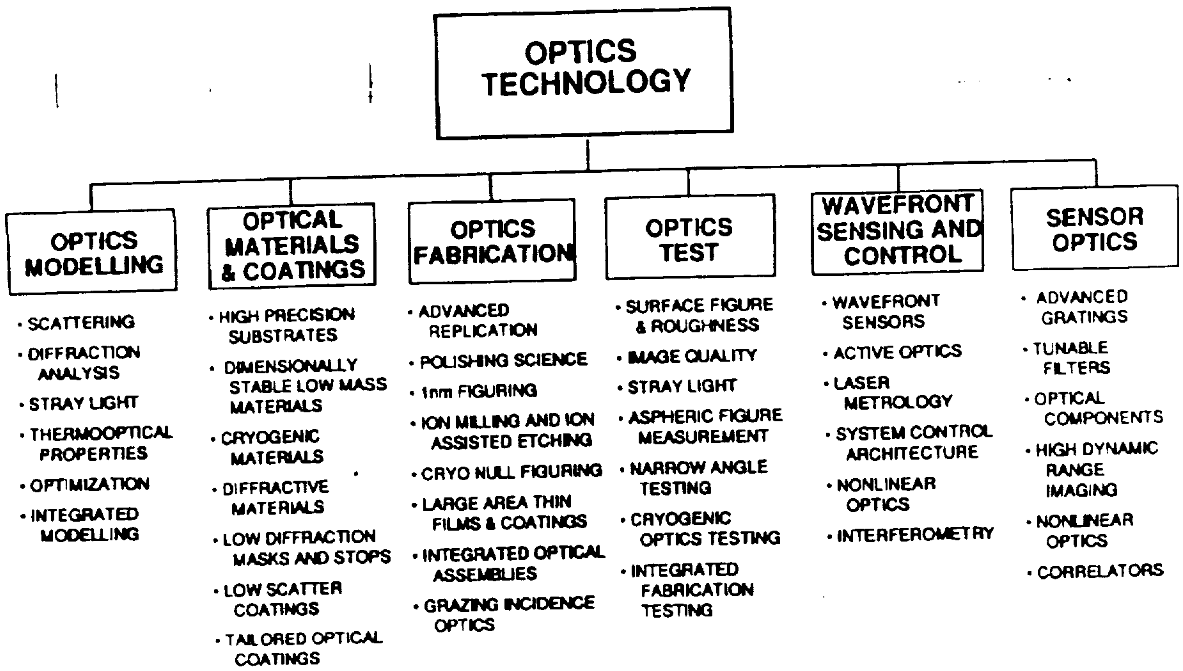
OPTICS TECHNOLOGY PROGRAM STRUCTURE



SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

SENSOR OPTICAL SYSTEMS

TECHNOLOGY ASSESSMENT AND CHALLENGES

Need	Assessment	Challenge
Radiometric Precision	1%	0.1%
Small cameras for Orbiters/Rovers	1 m^3	0.1 m^3
Low scatter light imagers	10^{-5}	10^{-10}
Adaptive Spectrometers	n/a	design, fabricate, test
Integrated Optics Imaging Spectrometer	n/a	design, fabricate, test

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SENSOR OPTICAL SYSTEMS

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

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SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

SENSOR OPTICAL SYSTEMS

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

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SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

SENSOR OPTICAL SYSTEMS

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

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SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

SENSOR OPTICAL SYSTEMS

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

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INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

COOLERS AND CRYOGENICS 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

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 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

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS & CRYOGENICS

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

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS & CRYOGENICS

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

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS & CRYOGENICS

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

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS & CRYOGENICS

AUGMENTED PROGRAM

- LONG LIFE VIBRATION FREE COOLER DEVELOPMENT
  - 65 K SORPTION AND BRAYTON
  - 10-30 K SORPTION AND BRAYTON
- 2-5 K LONG-LIFE MECHANICAL REFRIGERATION DEVELOPMENT

ATTRIBUTES	CANDIDATE TECHNOLOGIES
• 10-20 MW AT 2 K	• TURBO BRAYTON
• 50-100 MW AT 4-5 K	• J-T + UPPER STAGES
• LOW VIBRATION	• 4K STIRLING + UPPER STAGES
• LESS THAN 1 KW INPUT POWER	• MAGNETIC + UPPER STAGES

- DEMONSTRATE PROMISING ADVANCED COOLER TECHNOLOGIES
  - PARASITIC REDUCTION FOR SUPERFLUID HELIUM DEWARS
  - ADVANCED SUBKELVIN COOLER CONCEPTS
  - PULSE TUBE AND ADVANCED PASSIVE COOLER TECHNOLOGIES
  - FUNDAMENTAL COOLER PHYSICS RESEARCH

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS AND CRYOGENICS

FOCUSED TECHNOLOGY PERFORMANCE OBJECTIVES

2-5 K COOLER

MISSION REQUIREMENT	CURRENT SOA*	COOLER FOR SMMM, LDR	COOLER FOR SMMM,LDR
TEMPERATURE	1.5 - 2 K	2 K	4 - 5 K
COOLING POWER	30 mW	10 - 20 mW	50 - 100 mW
INPUT POWER	N/A	< 1 KW	< 1 KW
COOLER MASS	500 KG	< 50 KG	< 50 KG
VIBRATION	N/A	< 0.05 LBF	< 0.05 LBF
LIFETIME	< 1 YR	> 10 YR	> 10 YR
NEED DATE	FLOWN	2000	2000

*STORED LIQUID HELIUM

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS AND CRYOGENICS

FOCUSED TECHNOLOGY PERFORMANCE OBJECTIVES

VIBRATION-FREE COOLERS

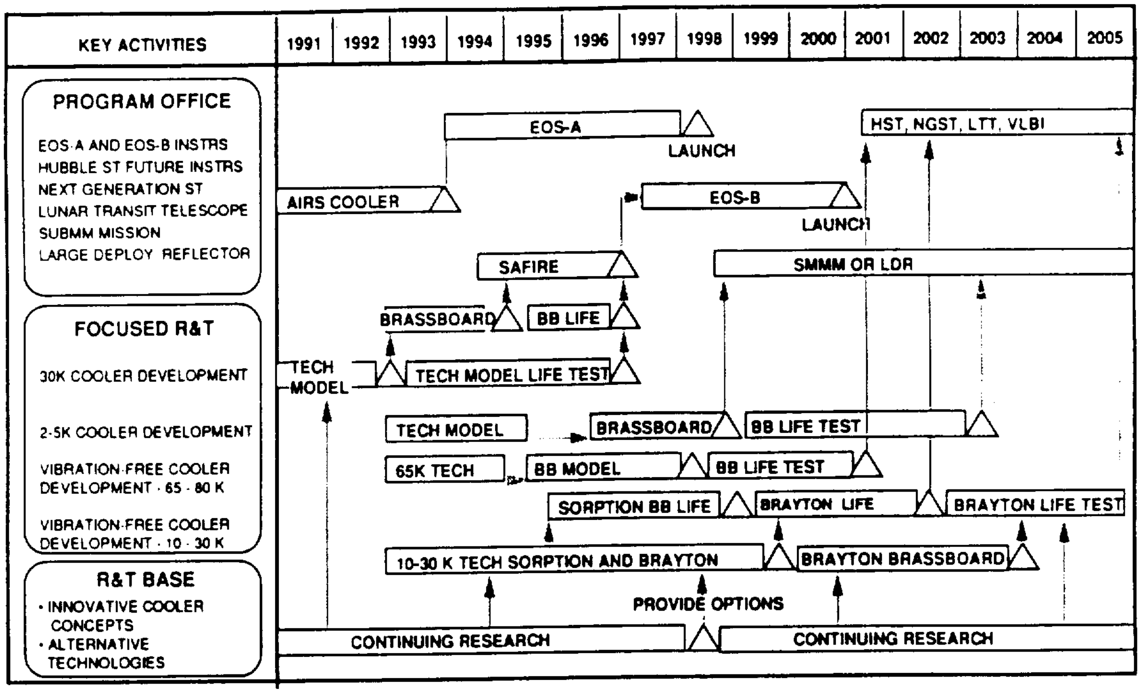
MISSION REQUIREMENT	CURRENT SOA*	COOLER FOR HST, LTT	COOLER FOR NGST, VLBI
TEMPERATURE	2 - 80 K	65 - 80 K	10 - 30 K
COOLING POWER	30 mW	1 W	20 mW
INPUT POWER	0	~ 100 W	~ 100 W
COOLER MASS	> 500 KG	20 KG	20 KG
VIBRATION	0	~ 0	~ 0
LIFETIME	~ 1 YR	10 YRS	10 YRS
NEED DATE	–	1998	2005

*STORED CRYOGEN COOLERS

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS AND CRYOGENICS

TECHNOLOGY ROADMAP/SCHEDULE



SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS AND CRYOGENICS

OTHER DEVELOPMENT EFFORTS

- **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**

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS & CRYOGENICS

FY93 AUGMENTATION

PRIORITIZATION:

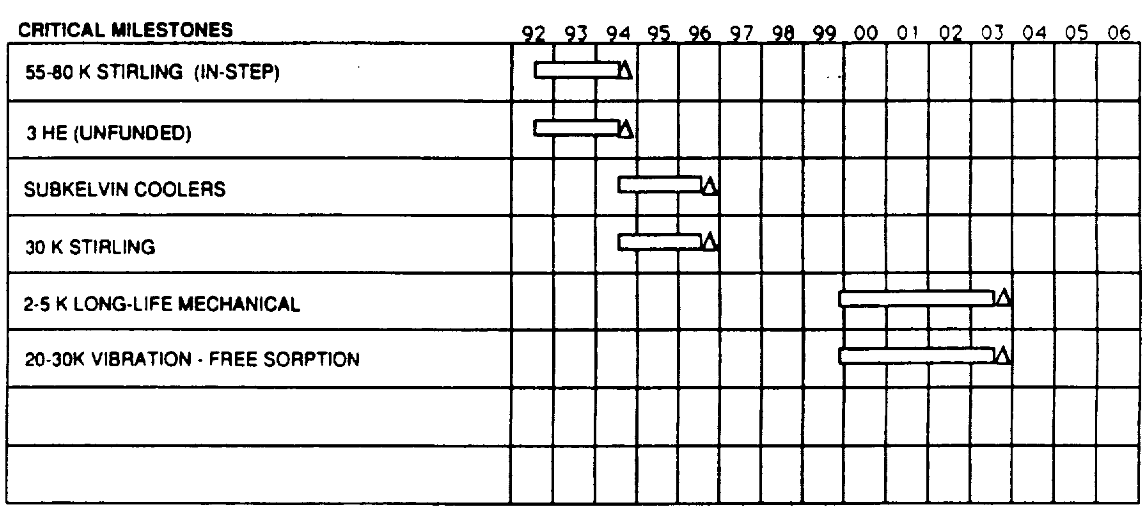
Focused Program

- 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 2K COOLER, UPPER STAGE
- VIBRATION FREE 65-80 K SORPTION COOLER

SPACE SCIENCE TECHNOLOGY: OBSERVATORY SYSTEMS

COOLERS & CRYOGENICS

COOLER FLIGHT EXPERIMENTS



COOLERS & CRYOGENICS

SUB-ELEMENTS	92	93	94	95	96	97	TOTAL
ON-GOING							
30 K STIRLING	3.2	3.7	3.9	1.6	1.4	1.5	15.3
PULSE TUBE COOLERS	0.5	0.6	0.6	0.6	0.6	0.6	3.5
SUBKELVIN COOLERS	0.1						0.1
ON-GOING - SUB-TOTAL	3.8	4.3	4.5	2.2	2.0	2.1	18.9
AUGMENTATION							
2-5 K LONG-LIFE MECHANICAL	0.0	2.0	2.0	2.0	2.4	2.4	10.8
VIBRATION - FREE 20-30 K SORPTION	0.0	0.7	0.8	1.5	1.5	1.5	6.0
VIBRATION - FREE 55-80 K BRAYTON	0.0	1.5	2.0	2.0	2.0	2.0	9.5
VIBRATION - FREE 2 K MAGNETIC	0.0	0.0	0.6	1.2	1.2	1.5	4.5
VIBRATION - FREE 2 K UPPER STAGE	0.0	0.0	0.0	1.2	1.2	2.2	4.6
VIBRATION - FREE 65-80 K SORPTION	0.0	0.0	0.0	0.0	0.0	1.0	1.0
AUGMENTATION - SUB-TOTAL	0.0	4.2	5.4	7.9	8.3	10.6	36.4
TOTAL	3.8	8.5	9.9	10.1	10.3	12.7	55.3

SSTAC/ARTS

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

OAET

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

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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

HIGH TEMPERATURE SUPERCONDUCTIVITY

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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.

HIGH TEMPERATURE SUPERCONDUCTIVITY

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SPACE APPLICATIONS OF HIGH TEMPERATURE SUPERCONDUCTIVITY

[illegible]	[illegible]	POWER AND PROPULSION
PASSIVE & ACTIVE MICROWAVE/mm WAVE COMPONENTS: FILTERS, RESONATORS, HI Q CAVITIES, TRANSMISSION LINES	IR DETECTORS	POWER TRANSMISSION LINES
SUBSYSTEMS: LOW NOISE AMPLIFIERS & RECEIVERS, PHASED ARRAY ANTENNAS	SIS & SNS MIXERS	ENERGY STORAGE: MOMENTUM WHEELS, SMES
DIGITAL SIGNAL PROCESSING	SNS SQUIDS THz LOCAL OSCILLATORS	ACTIVE BEARINGS FOR HYBROGEN ROCKET ENGINE TURBO PUMPS
	FPA VIBRATION DAMPING	
	FPA GROUNDING STRAP	
	CURRENT LEADS	
	PASSIVE MAGNETIC BEARINGS	

HIGH TEMPERATURE SUPERCONDUCTIVITY

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POTENTIAL PAYOFFS

- LOW LOSS, HIGHER SENSITIVITY MICROWAVE CIRCUITS
- REDUCED SIZE AND WEIGHT OF MICROWAVE COMPONENTS/SUSBSYSTEMS
- 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

HIGH TEMPERATURE SUPERCONDUCTIVITY

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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

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HTS PROGRAM ORGANIZATION

MICROWAVE & mm WAVE COMMUNICATIONS

- PASSIVE COMPONENTS
  FILTERS, RESONATORS, HI Q 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
  THz 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

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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

STATE OF THE ART:
- Films of YBCO & TBCCO 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

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

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 $0.8M REPROGRAMMED ANNUALLY AT LeRC) INSUFFICIENT FOR SUBSYSTEM DEVELOPMENT AFTER HTSSE II

COMMUNICATIONS APPLICATIONS STUDY

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- **Ku-B\ND AND Ka-BAND GROUND TERMINAL LOW NOISE RECIEVERS**
  - IMPROVE RECEIVER SENSITIVITY USING CRYOCOOLED 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

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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

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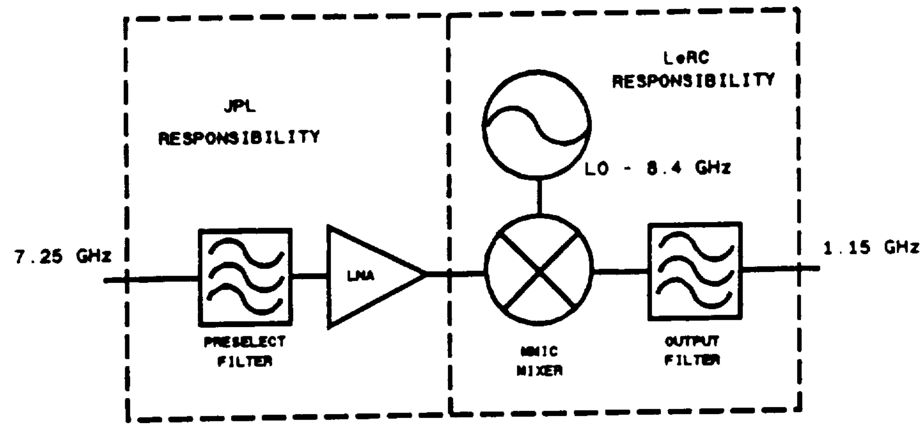
PROPOSED NRL/HTSSE-II EXPERIMENT
JOINT LeRC/JPL EFFORT



LOW NOISE RECEIVER SUBSYSTEM

CURRENT HTS PROGRAM - SENSORS

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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

JOSEPHSON JUNCTION DEVICES

APPROACH: Develop all YBCO SNS microbridges (edge junction weak link) for oscillators & mixers, BaKBiO SIS tunnel junctions for mixers

APPLICATIONS: SNS THz local oscillator & mixer for submm wave astronomy (ground-based observatories and flight missions - SMILS, LDR); SQUIDS 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

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**9 D*

CHALLENGES: Reduce noise & time constant (resistive), HTS SQUID magnetometer (inductance)

GOAL: > 10**10 D* @ 70-90K, single elts or arrays

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 GHs

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

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OBJECTIVE: 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=0 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 magnetic damping property of HTS ceramics

APPLICATION: Missions using Stirling cycle mechanical cryocoolers (EOS, 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 turboexpander efficiency (reduced power & heat leak); improved reliability and lifetime

MATERIALS: Levitation pressure adequate, some improvement in stiffness needed

NON-NASA: Recent advance 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

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TECHNOLOGY FIRSTS

- **AMONG FIRST IN U.S. TO DEPOSIT HIGH QUALITY YBCO FILMS BY LASER ABLATION**
- **FIRST TEST OF HTS Ka-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 BOLOMETER**

NASA PERSONNEL DOING STATE-OF-THE-ART HTS TECHNOLOGY DEVELOPMENT

HIGH TEMPERATURE SUPERCONDUCTIVITY

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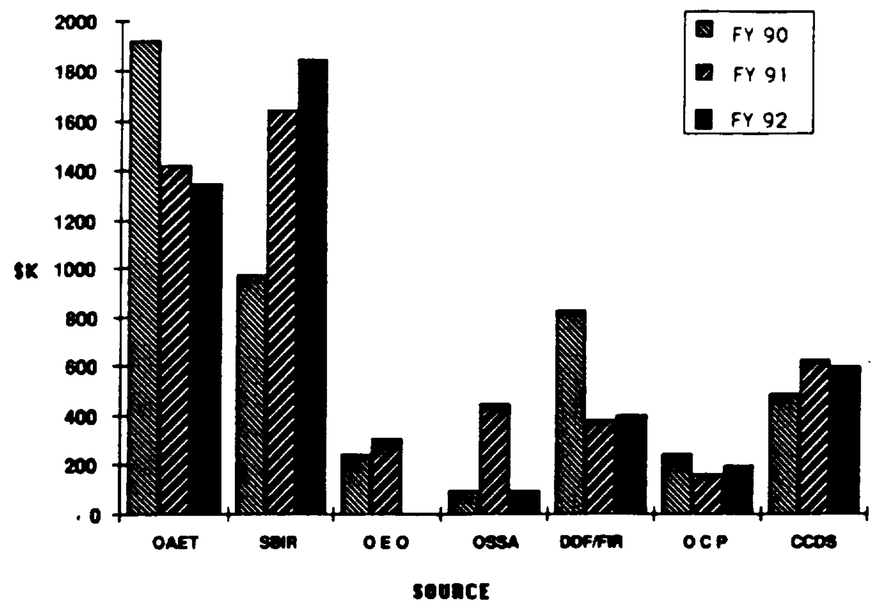
CURRENT FUNDING (FY 90-92)



FACILITIES

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NASA CENTERS HAVE THE NECESSARY FACILITIES ON-SITE OR READY ACCESS TO UNIVERSITY, GOVERNMENT OR INDUSTRIAL RESOURCES

STATE-OF-THE-ART CAPABILITES

- 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)

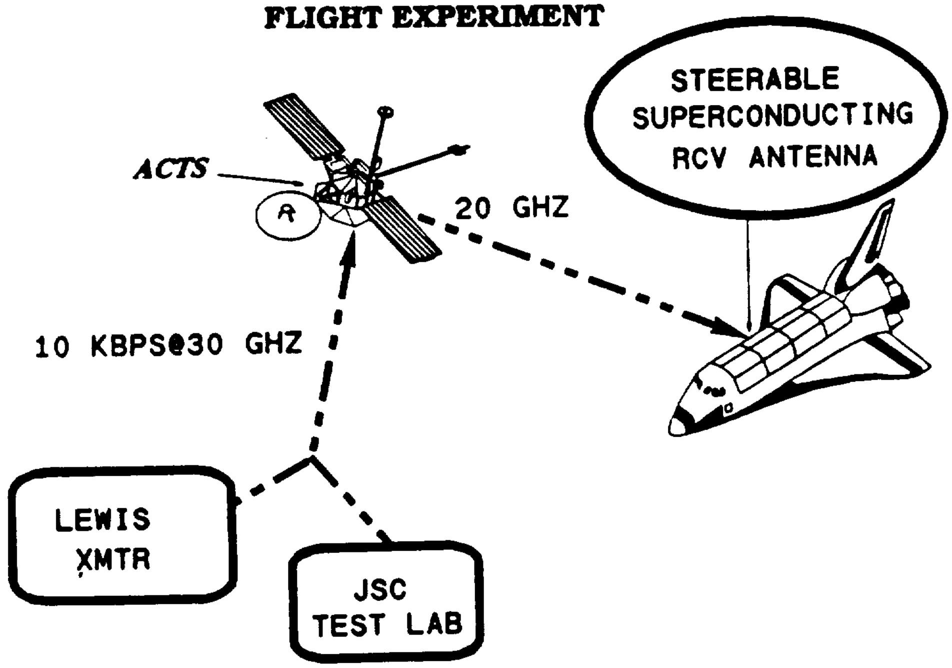
HIGH TEMPERATURE SUPERCONDUCTIVITY

HIGH TEMPERATURE SUPERCONDUCTIVITY
R&T BASE AUGMENTATION

- NEW INITIATIVES
- MILESTONES / RESOURCES

HIGH TEMPERATURE SUPERCONDUCTIVITY

ORBITER/ACTS HTS 20GHz PHASED ARRAY ANTENNA FLIGHT EXPERIMENT



ORBITER/ACTS FLIGHT EXPERIMENT OF HTS PHASED ARRAY ANTENNA

OAET

OBJECTIVE: DEMONSTRATE FUNCTIONALITY IN SPACE OF RECEIVER /PHASED 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

HTS DIGITAL SIGNAL PROCESSOR

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OBJECTIVE: Exploit HTS digital electronics for the next generation of smart comunications satellites

APPROACH: Develop a reproducable Josephon 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

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

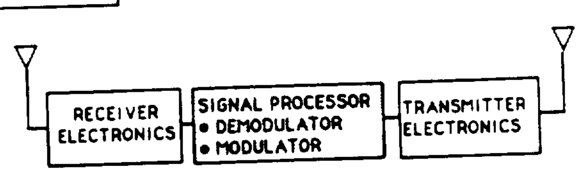
CHALLENGES:

- Processing of reliable, high density Josephson junctions

DIGITAL SIGNAL PROCESSOR

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 semiconductos subsystems
- Large increase in number of channels



SATELLITE TRANSPONDER

RESOURCES WITH AUGMENTATION

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CODE RC FUNDING IN M$

	FY91	FY92	FY93	FY94	FY95	FY96	FY97
BASE PROGRAM*	0.9	1.3	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
STRATEGIC PLAN AUGMENTATION	—	—	3.0	4.0	5.0	5.0	5.0
TOTAL	0.9	1.3	3.6	4.6	5.6	5.6	5.6
3X BUDGET AUGMENTATION	—	—	2.4	3.2	4.0	4.0	4.0
TOTAL	0.9	1.3	3.0	3.8	4.6	4.6	4.6

* REPROGRAMMED FROM COMMUNICATIONS BASE

AUGMENTED HTS PROGRAM MILESTONES & RESOURCE ALLOCATION

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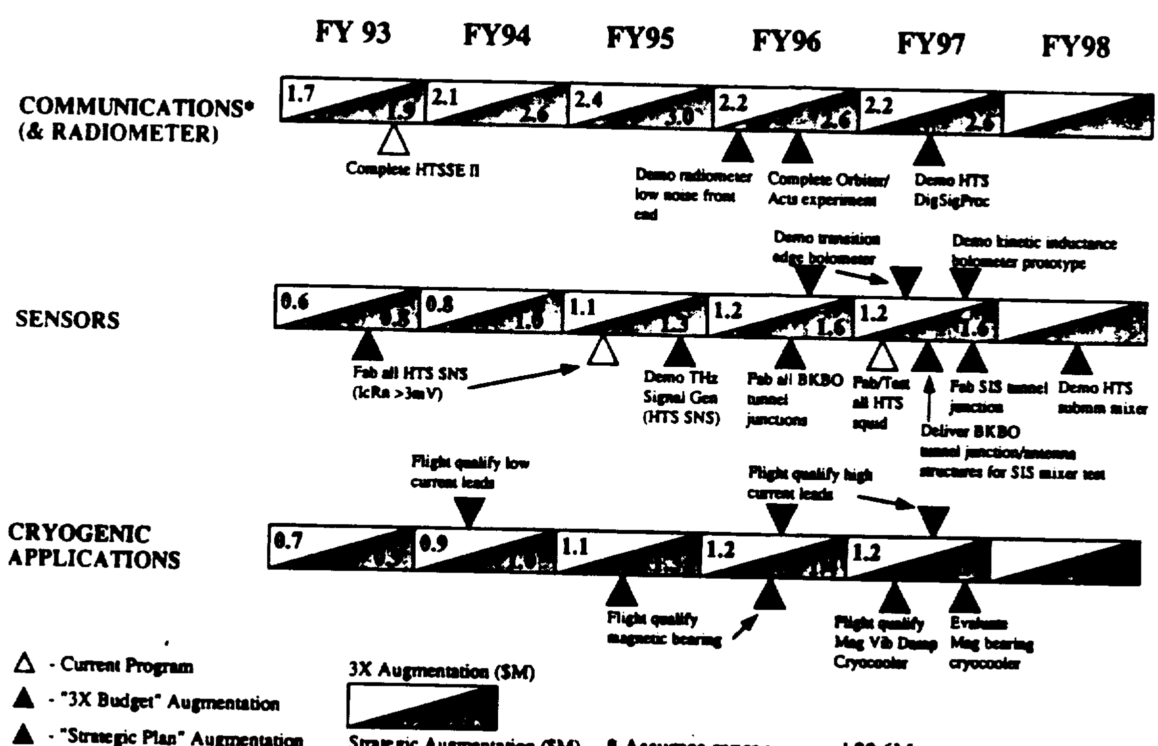

RELATED NON-NASA HTS EFFORTS

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- 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

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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

SUPERCONDUCTNG FOCAL PLANE ARRAY SIGNAL PROCESSING

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ON - ARRAY SIGNAL PROCESSING DEVELOPMENT STATUS (DEMONSTRATED WITH Nb)

- IR DETECTOR (TRW)
  - 10-25 uM
  - D* 10X better than best IR bolometer
- 12 BIT A-D CONVERTER (Westinghouse)
- 8 BIT SIGNAL PROCESSOR (Fujitsu, Hitachi)

DEVELOPMENT GOALS (SDIO)

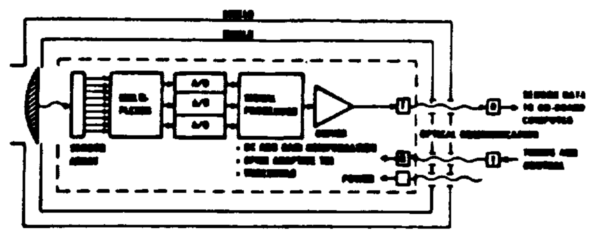
- END-TO-END DEMONSTRATION OF FPA ASSEMBLY WITH Nb (4K) DEVICES
- NEXT GENERATION - NbN (10K)
- FUTURE - BaKBIO (30K)

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



FOCAL PLANE ARRAY ASSEMBLY

ISSUES

OAET

- 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*