NAS8-39211

Automated Rendezvous And Capture Demonstration Study

Final Report

June 11, 1993

1.0 INTRODUCTION

This study was instituted to assist NASA and Marshall Space Flight Center (MSFC) in the development of ground and flight options to demonstrate the capability of Automated Rendezvous and Capture (AR&C). Study goals placed emphasis on low cost approaches and the need to be responsive to newly developing programs and studies such as Space Station Freedom and the Cargo Transfer Vehicle.

1.1 Purpose

This study provides an assessment of vehicle options and AR&C requirements to assist in the meaningful development of an AR&C capability.

1.2 Scope

This report documents study activities performed at Applied Research, Inc. (ARI) between April 1, 1992 and May 1993.

2.0 REQUIREMENTS

Automated Rendezvous and Capture (AR&C) is a mission operations function that is important to present and future space initiatives. Future space missions will potentially involve space station resupply, satellite refueling and servicing, spacecraft retrieval, crew rescue and spacecraft assembly in orbit. Thus, AR&C must closely track these developing initiatives to produce a demonstration applicable to a broad range of uses.

The initial requirements for AR&C were gathered from available studies, Space Station requirements and lessons learned from past NASA programs involving rendezvous and docking. Figure 2.0-1 shows the approach for determining flight and ground requirements. The initial requirements were documented in the AR&C System Requirements Document (SRD) dated May 29, 1992. Each requirement was identified as to its source to ensure traceability.

3.0 SPACECRAFT CARRIERS CONSIDERED

The demonstration of an AR&C capability was originally constituted as a ground program that would build a ground test bed at MSFC to test sensors, proximity operations techniques and docking hardware. This test bed worked in conjunction with test facilities and programs at JSC for items such as the Global Positioning System (GPS) and the laser-operated Trajectory Control Sensor (TCS), currently being developed for the Shuttle program. Working together, the MSFC and JSC facilities offered a repetitive test environment that would develop AR&C systems and test them at close proximity. Figures 3.0-1 and 3.0-2 list the AR&C facilities available for test support at MSFC and JSC.

A conference in Williamsburg, VA in 1991, however, considered that the limitations of the ground facilities mandated a flight demonstration to provide the proper confidence to future programs in AR&C systems development. As a result, an effort was initiated in early 1992 to evaluate methods and costs for performing a flight demonstration. Figure 3.0-3 lists typical proposals and options considered.

4.0 GROUND AND FLIGHT OPTIONS

The flight options were first evaluated for the technical capability to meet AR&C objectives. The list of options was then evaluated for cost. Figure 4.0-1 shows typical technical trades evaluated and a reduced group of flight options. The Shuttle Pallet Satellite (SPAS) option was proposed as a joint program by the European Space Agency (ESA) as a result of discussions at NASA Headquarters. This option proposed to modify existing ASTROSPAS spacecraft to provide the chaser and target vehicles. NASA would mount their AR&C hardware on the chaser, as would ESA, and a joint mission would be conducted. The SPAS option offered attractive cost-sharing opportunities for both ESA and NASA.

The range of costs, if NASA produced the chaser vehicle, was $86-95M excluding launch costs. After negotiations with ESA, NASA cost (shared) was reduced to about $62M including launch costs, and a final program of $50.9M excluding launch costs, was defined. This offered NASA a lower cost approach that met budget guidelines and still fulfilled AR&C requirements. The joint ESA/NASA program was chosen for the flight demonstration.

A major objective of the AR&C program is to provide a ground test bed that will be capable of full AR&C flight performance evaluations and of limiting the risk of developing future AR&C systems. Data from the flight demonstration will be used to validate the ground demonstration and provide confidence in future AR&C performance evaluations. The ground demonstration consists of a flat floor facility with 6 degree-of-freedom (6-DOF) mechanisms to control movement of the chaser and target. Resident software in the facility computers provides the drive commands to the 6-DOF facility. The ground test bed is expected to provide evaluations of proximity operations sensors; develop ground and flight operations procedures; develop GN&C and collision avoidance software; add to the skills of the developers and provide evaluation facilities; and provide performance data. The flight demonstration is expected to provide proof-of-concept; flight performance and ground facility validation; flight qualification of some elements (i.e. GPS, software, docking mechanism); and operation of the AR&C systems in a real flight environment.

5.0 JOINT ESA/NASA MISSION

ESA and NASA are negotiating a Memorandum of Understanding (MOU) on which to base the performance of the joint AR&C mission. Figure 5.0-1 lists the program objectives contained in the MOU. Figure 5.0-2 lists the mission requirements that are expected to be accomplished by the performance of the mission. Each agency has negotiated responsibilities that match their funding agreements and these responsibilities are scoped in Figure 5.0-3.

A relative motion plot of the ESA and NASA flight profile is shown in Figure 5.0-4. The ESA MINI-CHASER and ASTROSPAS target will be launched to orbit by the Space Shuttle. The remote manipulator arm (RMS) of the Shuttle will deploy the MINI-CHASER and ASTROSPAS as a unit. The Shuttle will then back off, allowing the chaser and target to separate and begin the 30 hour mission (approximately). The chaser will translate to a point 2km from the target and the operations shown in the profile will begin. The chaser contains pre-programmed software capable of performing each mission function without ground support. On board sensors allow the chaser to determine its orbital (absolute) and relative position with respect to the target. All of the profile operations will be closely monitored by the ground control team in the SPAS Operations Center (SPOC).

The joint work requirements for the AR&C program are shown in Figure 5.0-5. ESA will function as the overall mission manager and will control all AR&C flight and ground operations. Both ESA and NASA provide an AR&C package containing the sensors and GN&C software to complete the rendezvous and docking operations. NASA supports ESA in their mission manager role and provides the Shuttle launch.

NASA has organized the AR&C program as a multi-center, cooperative effort involving the launch center (KSC) and two of the design centers (MSFC and JSC). Figure 5.0-6 lists the responsibilities assigned to each center. Several future decisions coming in early 1994 will affect some of these tasks. A sensor comparison test (or fly off) will occur in early 1994 that will select only one sensor for the flight demonstration, either the TCS of the VGS. Also, at about the same time, a decision will be made as to whether or not to complete the flight demonstration. This decision is being determined by budget considerations. A ground demonstration program is proceeding with the option of completing the flight demonstration if funding is allocated in the 1994 budget. If not, the ground demonstration will be completed. A schedule of these activities is shown in Figure 5.0-7.

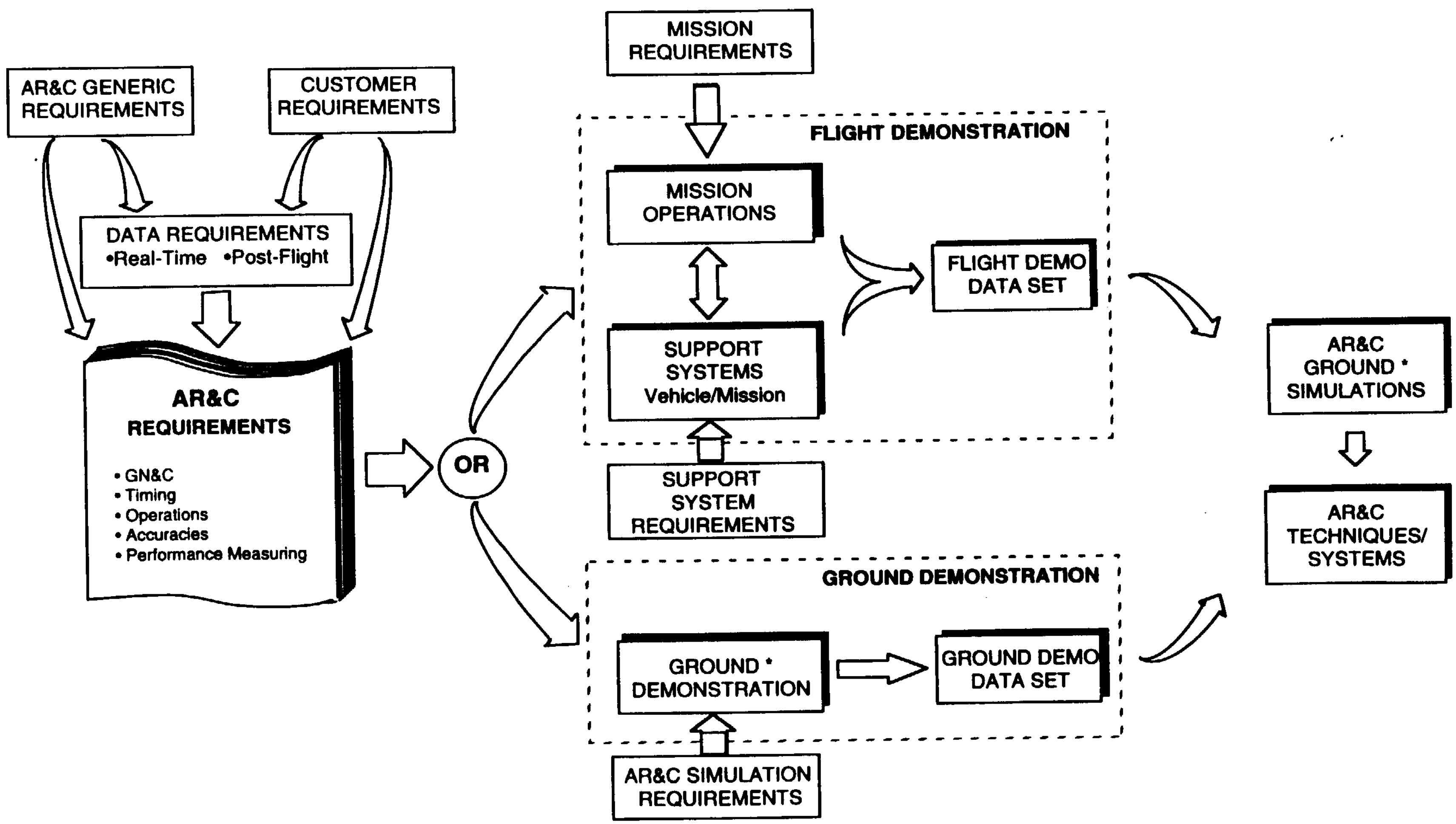
6.0 SUMMARY

In the past year, NASA's AR&C demonstration program has evolved from a study of potential options to the definition of a joint demonstration mission with ESA and the initial development of a ground test bed for future AR&C user evaluations. Initial evaluations, to use in-orbit assets such as Explorer and EURECA II as docking targets with NASA building a chaser vehicle, proved too costly for available budgets. A proposal by ESA offered a solution for a flight demonstration while maintaining the development of the AR&C ground test bed. This joint mission is presently under development.

Program planning has produced an initial AR&C NASA Project Plan and a preliminary NASA system requirements document. ESA is preparing joint documentation for the projects (Joint ESA/NASA Project Plan and Joint System Requirements Document) and will review the initial drafts at the System Requirements Review (SRR) in Europe, scheduled for June, 1993.

This report addresses only the first year of a program that will not be completed until FY98. The basic groundwork has been completed and activities are in progress to select a prime support contractor. The AR&C Program is small in terms of dollars, mission length and hardware, but it does have the same NASA-internal and international interfaces as larger programs such as Spacelab or Space Station. As such, the AR&C program presents an interesting challenge for controlling cost and schedule, meeting technical objectives and doing this with the limited flexibility of a small project.

FIGURE 2.0-1 AR&C REQUIREMENTS DERIVATION/VERIFICATION



* NOTE: AR&C Ground Simulations Evolve From Ground Demonstration

FIGURE 3.0-1 MSFC FACILITIES

Facilities	Applications	Range	Remarks	Status
Flight Robotics Laboratory/Flat Floor Facility	Open and closed loop 6 DOF test, sim & demo's of full size S/C, sensors, cold gas thrusters, docking mechanisms and subsystems	0-50 M	6 DOF air bearing, 6 DOF overhead crane (500 KG capability) solar illumination (dynamic upgrade in plan), full safety constraints	Fully operational, in use (TRS, OMV, TPDM, CTV)
Space Operations/Mechanisms Test Bed	• Full scale high fidelity hardware in the loop contact and body dynamics using vertical hydraulic stewart table	0-2 M	6 DOF platform capable of up to 9 tons over ± 1 M translation at ± 25 degrees attitude, 8 HZ using force moment feedback, full safety constraints	Fully operational, in use (TRS, OMV, SSF, CTV, HST, RMS, TPDM)
	• Software modelling of mechanisms, sensors, orbital dynamics, control, algorithms, automated or man-in-the-loop	0-Open ended	Silicon graphics display, computer connected to 6 DOF stewart table for force and moment feedback for H/W eval.	Fully operational
Coherent Doppler LIDAR Development Facility	Development lab providing technology base for LIDAR system providing for acquisition and rendezvous sensor replacing GPS for targets without GPS	0-100 KM	Development lab	Operational with on-going wind measurement system in place
Stray Light Vacuum Tunnel	Sensor testing chamber (3MX12M) with 100M tunnel connecting target and retro-reflector chamber	100 M Length	Straylight/solar and light efficiency evaluation for video guidance sensor and laser radar evaluation/test	Facility upgrade in process, limited use in 93, fully operational in 94
RF Antenna Range	RF radar and tracking analysis, design, development, test and evaluation as well as command/telemetry system design, development, test, evaluation and engineering	120/ 800 M	Test and development facility, 108000 cubic feet microwave anechoic chamber, bench laboratories	Fully operational (STS, HST, OMV/CTV, NLS)
Thermal/Vacuum/Vibration /Modal/Acoustic/Loads	System analysis, qualification testing, modal surveys, etc.	N/A	Full complement of facilities to support full scale development including SSF modules	Fully operational
Avionics System Testbed	Develop and evaluate new technologies of flight hardware and software in support of new MSFC programs	N/A	Three axis table for optical and inertial stimulus of sensors. Large hybrid computer for analytical evaluation of avionics systems	First phase operational buildup in progress
Institutional/Support	Design, development, fabrication, assembly, analysis, mission operations, testing and evaluation, safety and qualification	N/A		

FIGURE 3.0-2 JSC FACILITIES

Facilities	Applications	Range	Remarks	Status
Precision Six-Degree-of-Freedom Test Facility	Precision DDT&E static and dynamic tests for laser radar and image based tracking systems	0-12 M	Calibrated rail mounted on granite. Two axis sensor positioner, three axis target positioner, master computer	Active
Global Positioning System (GPS) Laboratory	DDT&E and static and dynamic tests for GPS tracking and navigation components, subsystems and systems for space application	N/A	450 soft laboratory utilizes adjacent boresight and antenna range. Two 8-channel CA code, two 4-channel P-code and one 10-channel receivers, 10-channel GPS signal simulator, Software tools	Active
Inertial Systems Laboratory (ISL)	Configuration controlled facility. Evaluation & calibration of inertial sensors and systems. Accurate and precise control (Static or dynamic) position, rate, and acceleration. Shuttle IMU, ACIP, RGA's and star tracker calibration	N/A	Dynamic motion simulator (DMS) 3-axis servo, ROTAB 2-axis table, 5 hp 2100 and 2 masscomp computer systems, ADS 100 interface to KSC	Active
Inertial Components Laboratory (ICL)	Evaluation & calibration of inertial sensors and systems. Accurate and precise control (Static or dynamic) position, rate, and acceleration	N/A	Fecker 252 air bearing table 2-axis, precision readout, Goertz air bearing table 2-axis, ultraprecision readout. Three dividing heads and several PC's for data acquisition/reduction	Active Goertz table being upgraded
Electro-Optics Laboratory (EOL)	Optical/electro-optical testing and evaluation, star tracker testing, metrology, photometry, imaging, data processing and design	N/A	Five optical benches, three microflat tables, 2-axis position table, target star field simulator, digital photometer, light calibration standards, rubidium clock, microprocessor development station, workstation and software tools	Active

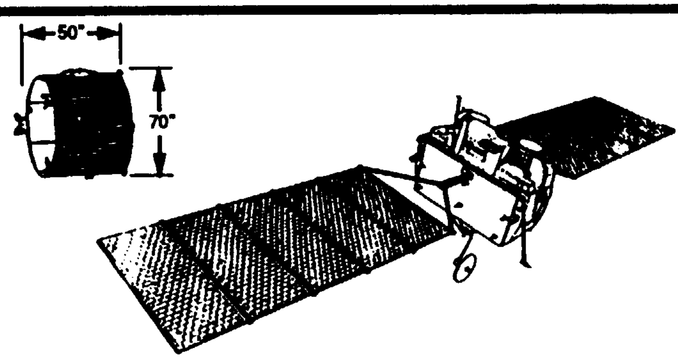
FIGURE 3.0-3 AR&C FLIGHT DEMO PROPOSALS AND OPTIONS (1 OF 2)

FLIGHT DEMO	DESCRIPTION	LAUNCH VEHICLE (CHASER)	LAUNCH VEHICLE (TARGET)	REMARKS
EURECA II Target / Small Sat. Chaser	EURECA II modified with GPS, targets, docking hardware Modified small sat. class S/C : GPS, dock mechanism,RCS, sensor,etc.	STS	STS	
EURECA II Target / Small Sat. Chaser	EURECA II modified with GPS, targets, docking hardware Modified small sat. class S/C : GPS, dock mechanism,RCS, sensor,etc.	ELV	STS	
EURECA II Target / MMU Chaser	EURECA II modified with GPS, targets, docking hardware Add AR&C module to unmanned MMU	STS	STS	AR&C module includes GPS, dock mechanisms, sensor, etc. Range limited to approx. 6 miles
Explorer Platform Target / Small Sat. Chaser	Explorer platform modified with GPS, targets, docking hardware Modified small sat. class S/C : GPS, dock mechanism,RCS, sensor,etc.	STS	ELV	
Explorer Platform Target / Small Sat. Chaser	Explorer platform modified with GPS, targets, docking hardware Modified small sat. class S/C : GPS, dock mechanism, RCS, sensor, etc.	ELV	ELV	

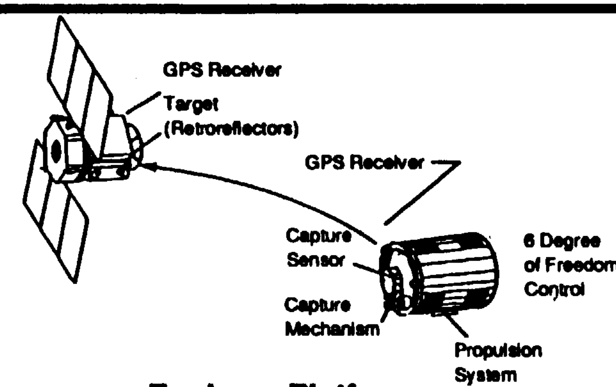
FIGURE 3.0-3 AR&C FLIGHT DEMO PROPOSALS AND OPTIONS (2 OF 2)

FLIGHT DEMO	DESCRIPTION	LAUNCH VEHICLE (CHASER)	LAUNCH VEHICLE (TARGET)	REMARKS
SPAR Target / Small Sat. Chaser	SPAR modified with GPS, targets, docking hardware Modified small sat. class S/C : GPS, dock mechanism,RCS, sensor,etc.	STS	STS	
SPAR Target / Small Sat. Chaser	SPAR modified with GPS, targets, docking hardware Modified small sat. class S/C : GPS, dock mechanism,RCS, sensor,etc.	ELV	STS	
SPAR Target / MMU Chaser	SPAR modified with GPS, targets, docking hardware Add AR&C module to unmanned MMU	STS	STS	AR&C module includes GPS, dock mechanisms, sensor, etc. Range limited to approx. 6 miles
MMU Target / MMU Chaser	MMU modified with module containing GPS, targets, docking hardware Add AR&C module to unmanned MMU	STS	STS	AR&C module includes GPS, dock mechanisms, sensor, etc. Range limited to approx. 6 miles
STS Target / MMU Chaser	Add AR&C module to unmanned MMU	STS	STS	Potential safety constraints on automated approach of MMU to STS may limit demo goals

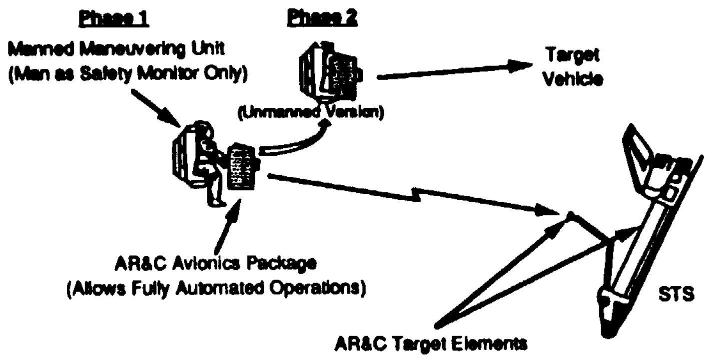
FIGURE 4.0-1 TYPICAL FLIGHT DEMO OPTIONS



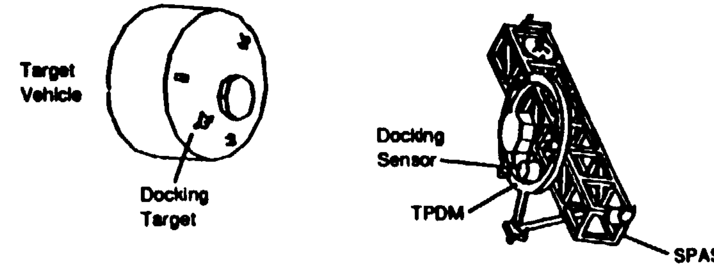
EURECA



Explorer Platform



Manned Maneuvering Unit (MMU)



Shuttle Pallet Satellite (SPAS)

TRADES TO BE PERFORMED

Launch Vehicle: STS, ELV

Target: Existing/Modified, New

Chaser: Existing/Modified, New

Disposition: Leave/De-orbit, Retrieve

Flight Phases Demonstrated: Phasing, Rendezvous, Proximity Operations, Standoff, Capture, Abort

Components/Elements: Guidance, Navigation & Control Mechanisms; Mission & Vehicle Management Sensors

Onboard vs Ground: Control

FIGURE 5.0-1 AR&C PROGRAM OBJECTIVES (MOU)

(a) Contribute to the Future Capability to Conduct Unmanned Spacecraft Operations with Space Station Freedom;

(b) Demonstrate Spacecraft Automated Rendezvous, Proximity Operations, Station Keeping and Capture with a Designated, Cooperative Target;

(c) Demonstrate the Safety of Automated Rendezvous and Capture Including Recovery from Anomalous Situations;

(d) Validate Ground Simulation Tools by Flight Demonstration;

(e) Develop Expertise, Knowledge and Skills Necessary to Build an Operational AR&C System;

(f) Establish the Functional Performance Capabilities of the Individual System Elements and of the Integrated AR&C System;

(g) Reduce Future Program Cost and Risk by Providing AR&C Products Developed from the Joint Program;

(h) Demonstrate Application of Relevant Technology for Future AR&C Systems and Missions;

(i) Contribute to the Achievement of Inter-operability of Resupply Vehicles Serving Space Station Freedom;

(j) Provide Design Criteria, Operational Procedures and Flight Techniques Which Will Influence Standardization of Appropriate Aspects of AR&C Systems; and

(k) Establish a Test Bed and Test Procedures That Will Validate Future AR&C Systems Prior to Flight.

FIGURE 5.0-2 AR&C MISSION REQUIREMENTS (MOU)

(a) Automated Rendezvous

(b) Soft Dock

(c) Absolute/Relative Navigation

(d) Proximity Operations

(e) Acquisition/Reacquisition

(f) Precision Standoff (Station Keeping)

(g) Collision Avoidance Maneuver

(h) Flight and Ground Operations

(i) Approach and Departure Strategies

FIGURE 5.0-3 SCOPE

» Overall AR&C Mission Management Integration

» Design, Develop, Integrate, and Test a MINI-SPAS Chaser, ASTROSPAS Target, and AR&C Hardware/Software Package

» Ground Simulation Support and Validation

» Conduct ESA/NASA Integration Test

» Flight and Ground Operations

» Design, Develop, Integrate, and Test an AR&C Hardware/ Software Package for Installation on ESA MINI-SPAS Chaser and ASTROSPAS Target

» Multi-Center Program to Support AR&C Flight Demonstration

» Technology Demonstration, Not Advanced Development or Operational Program

» Flight and Ground Operations

» Ground Simulation Support and Validation

FIGURE 5.0-4 ESA/NASA FLIGHT PROFILE

Flight

ESA - Two Docks

NASA - Two Docks one Fly Around

Both-Relative Navigation with Sensors and GPS

SS - Communication Relay

Ground

ESA SPOC

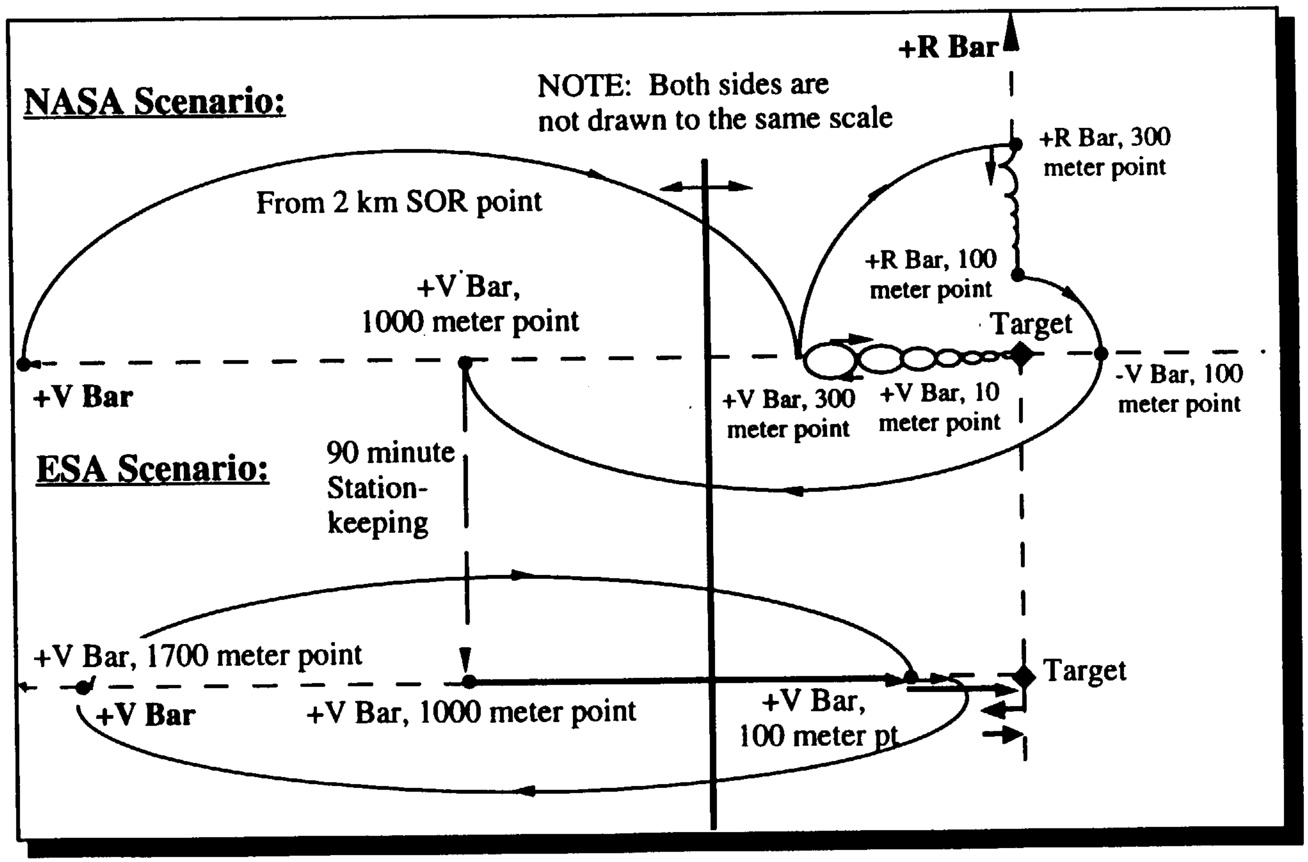


FIGURE 5.0-5 ESA/NASA JOINT WORK REQUIREMENTS

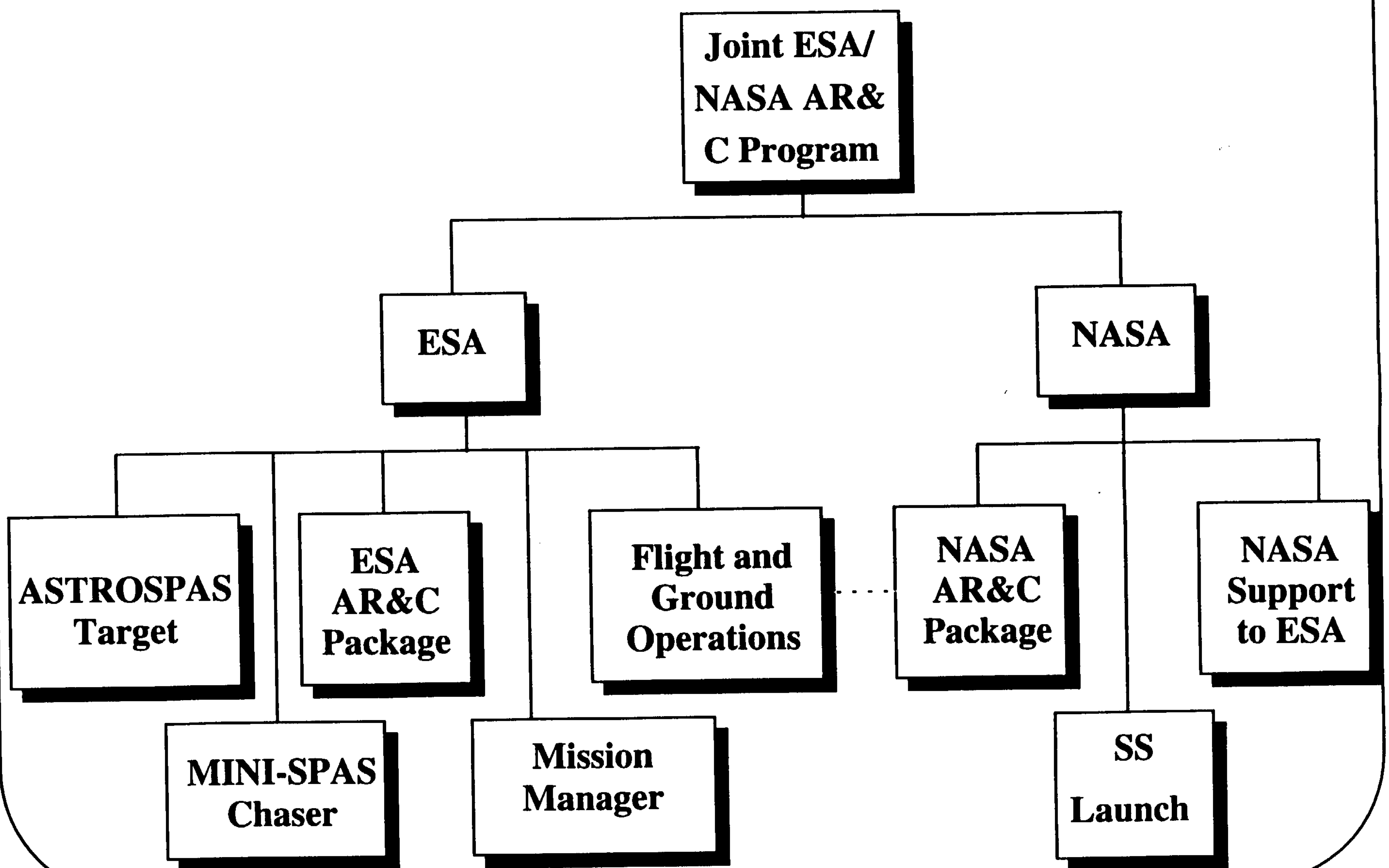


FIGURE 5.0-6 AR&C CENTER RESPONSIBILITIES

- AR&C Project Management
- NASA AR&C Package Development, Integration, and Test
- VGS Sensor/Computer/TPDM/Flight Software Design and Development
- Operate Ground Facilities and Simulations for Flight Support
- Support SPOC Mission Simulations
- Support Real Time Operations
- AR&C Test Bed Development
- Mission Simulation Support at ESA SPOC(@KSC)
- NASA Configuration Control
- NASA Performance Analysis Report
- ESA Liaison

- AR&C Flight and Ground Operations
- TCS Sensor
- GPS Testing and Simulation
- Develop and Operate Ground Facilities and Simulations
- Support GN&C and Flight Software Design and Development
- Develop Unique SPOC Software for AR&C
- Flight Operations Training & Support SPOC Mission Simulations
- Support Real Time Operations

- Launch Site Checkout and Processing
- Recovery of AR&C Flight Elements
- SPOC Facility Location

AR & C PROGRAM SCHEDULE

6 MAY 1993