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DEVELOPMENT AND APPLICATION OF A RENDEZ-VOUS AND DOCKING SENSOR „RVS“

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ABSTRACT: *RVS shall serve as a docking sensor for the docking process of the European Automatic Transport Vehicle (ATV) on the International Space Station (ISS). It was developed by Jena-Optronik Company (DJO) - Prime Contractor and Dornier Satellitensysteme (DSS) in the frame of an ATV Rendezvous Predevelopment Program (ARP) charged by the European Space Agency (ESA).*

RVS has been qualified for NASA Shuttle Mission, and was - integrated into the docking module of Shuttle „Atlantis“ - accompanying the docking and retreat procedures of the Shuttle during the STS-84 and STS-86 missions to the MIR Station with Range, Line of sight and Attitude measurements. Thus, first results from RVS application under real Space conditions are available.

RVS consist of active and passive elements. The active ones - sensor head and electronics unit - are mounted on the chaser vehicle. They emit laser light, receive and process the reflected light. The passive one - the Target - is arranged in a defined pattern reflecting the light emitted by the active part of RVS.

Working as a scanning laser radar, RVS performs a time of flight measurement of laser light and determines the line of sight values of the target pattern by scanning the laser beam over certain scan windows. An attitude determination of the target pattern wrt the coordinate system of the optical head is performed for short ranges evaluating the measured range and line of sight values.

Data processing within RVS guaranties automatical acquisition and track over a range of about one meter up to nearly one thousand meters under complicated outer conditions, including separation of reflected laser light from cw light, elimination of invalid returns, and automatic re-acquisition in case of target loss.

An RVS data rate of two Hertz combined with range and angular values of high accuracy are excellent presuppositions for rendezvous and docking guidance

1 INTRODUCTION

The ATV (Automated Transfer Vehicle), being a logistic/re-supply vehicle for ISS (International Space Station), needs a qualified Rendez-Vous Sensor (RVS) in order to perform the required highly automated rendezvous mission objectives. Therefore, it was necessary to develop and validate new sensor concept technologies in the frame of a ATV Rendezvous Predevelopment Project (ARP) in order to minimise the risks associated with their use during the ATV mission, by pre-developing them at an early development stage, support and lower the development risk, and secure the ATV development, verification and validation processes.

The ARP Project has been composed of three major blocks:

- the ARP Kernel including all system level activities covering the development, verification and validation steps of the Rendez-Vous and Docking (RVD) technologies, as a major system function for ATV
- the ARP Rendez-Vous Sensor (RVS) development, for ground simulation/verification and in-flight demonstration,
- the ARP GPS Receiver procurement, for ground simulations and in-flight demonstrations.

This paper is going to describe the second of the major blocks mentioned above: Results of the RVS development as well as on-ground and in-flight verification.

2 EQUIPMENT CONCEPT

The task of the Rendez-Vous Sensor (RVS) is to provide the measurements necessary to support the proximity operation (approach and departure) of a chaser spacecraft to a target spacecraft within a vicinity of about 1.000 m around the target spacecraft.

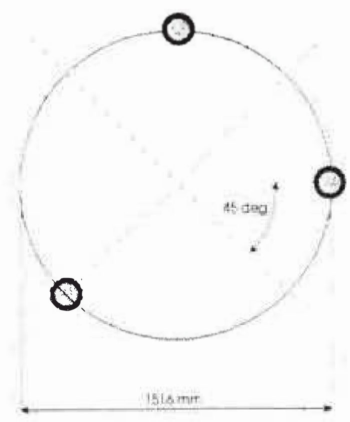


Fig 1: Geometry of the ARP-RVS Target Pattern

The target spacecraft carries the passive RVS constituent: a Target Pattern (TP) consisting of three retro reflectors (corner cubes) with a diameter of 25 mm each, arranged in a three-angular manner according to Fig. 1 and reflecting the light emitted by the active element.

The active RVS constituent (from now on called „RVS" only) is mounted on the chaser spacecraft. RVS works as a Scanning Laser Radar emitting pulsed laser light, receiving and processing the light reflected by the target pattern. Thus, RVS is able to determine range (R) values from a sophisticated time-of-flight measurement of a pulsed laser beam. Line-Of-Sight (LOS) angle values are derived from the angular position of the RVS scan mirrors at the time the laser beam hits the TP and - in the last phase of the approach from 40 m downwards to contact - also the relative attitude Pitch, Yaw and Roll between chaser and target space vehicle are computed. Pitch and yaw are calculated from the single retro range values, Roll is derived from single retro LOS values (in both cases considering other values).

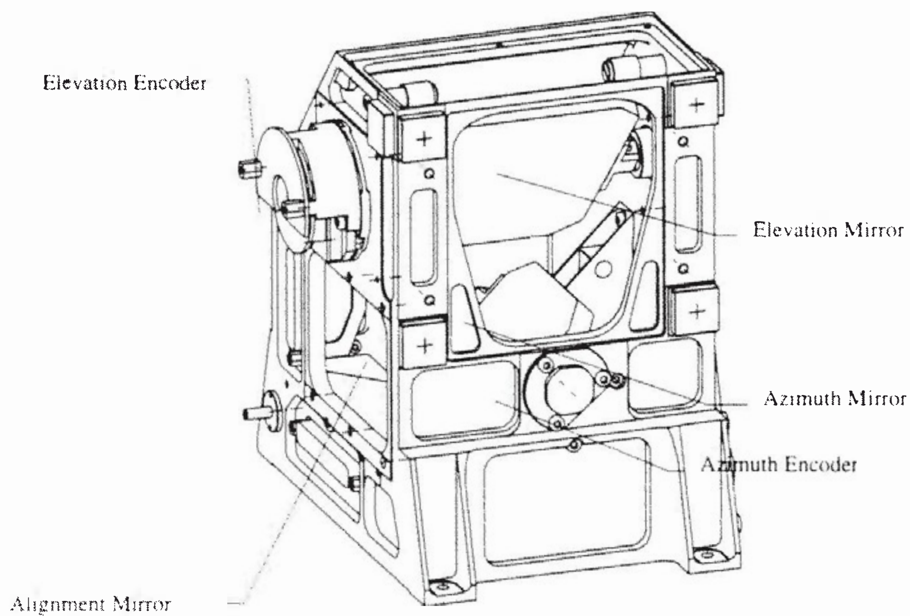


Fig. 2 RVSH Front View - Integration not yet completed

The RVS (i.e. the active part mounted on the chaser) is composed of two major constituents: the RVS Optical Head (RVSH), the RVS Electronic Unit (RVSE). RVSH and RVSE are connected by two electrical and two optical fibre cables. All other electrical interfaces (RVS to the „rest of the world") are located on the RVSE.

RVSH (see Fig. 2 and Fig. 3) comprises the following main components: housing, transmitter optics (Tx), receiver optic (Rx), two scan motors for azimuth and elevation respectively, two scan mirrors for azimuth and elevation respectively, two angular encoders for measurement of the azimuth and elevation angle. Alignment mirrors serve for adjustment aids of RVSH.
The main parameters of RVSH are given in Table 1.

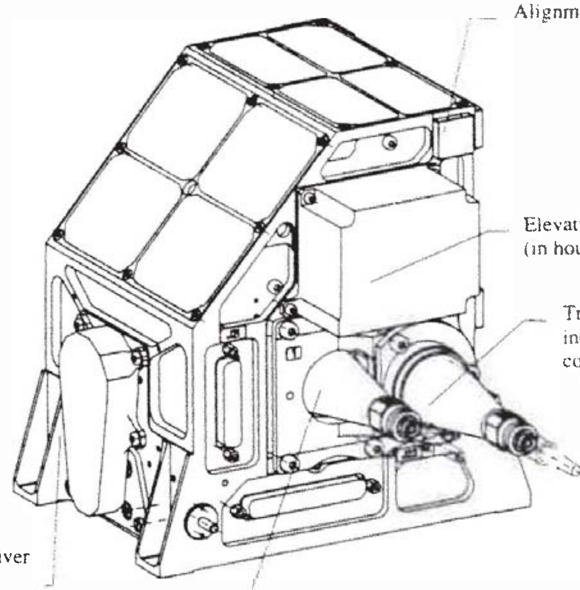


Fig. 3 RVSH rear view

RVSH housing	outer dimensions mass material	184x240x160mm³ 3.1 kg Aluminium alloy
Scan mirrors	2 orthogonal arranged mirrors: maximum useful scan angle material of mirror bodies reflecting surfaces outer size mass (light weighting structure) axes ball bearings	Elevation Mirr. (EM), Azimuth Mirr.(AM) ± 15 deg (AM, EM) Aluminium alloy diamond milled, Gold coated 106 x 79 mm² (EM) 52 x 65 mm² (AM) 72.6 g (EM), 29.0 g (AM) driven via metal belts coated with a MoS_2 lubricant
Tx, Rx :	focal length clear aperture distance of the opt. axes	80 mm 30 mm 33 mm
Optical fibres	 core diameter cladding diameter numerical aperture	Laser diode, photo-detector to the optics 200 µm 280 µm 0.22

Tab. 1 Main parameters of RVSH

RVSE contains the following components: the Laser Range Finder (LRF) with the modules Transmitter Board (Tx), Receiver Board (Rx), and Signal Evaluation Board (SE): the MicroProcessor Board (MP), the Scanner Control (SC) with the modules Scanner Control Electronics Board (SCE) and Scanner Control Interface Board (SCI); the External MIL-STD-1553B Interface Board (IF); and the Power Supply (PWR) with the modules PWR1 and PWR2.

The RVSE components mentioned above are arranged in the Electronics box. A block diagram of RVSE is given in Figure 4.

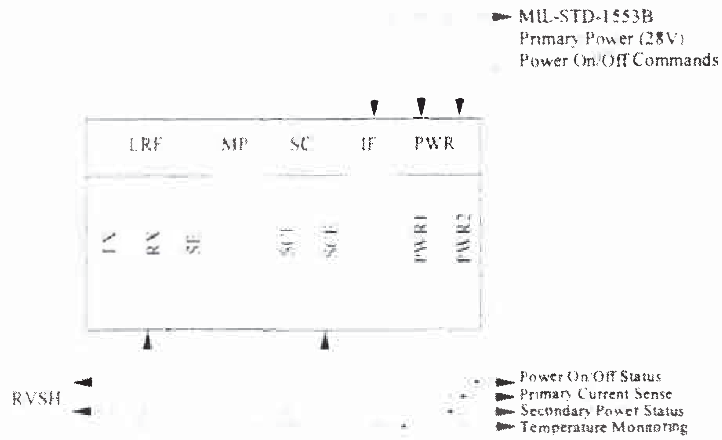


Figure 4: Block Diagram of the RVS Electronics Unit (RVSE)

Table 2 summarises the main parameters of RVSE.

Laser Rangefinder	transmitter diode	GaAs single stripe Laser diode
	wave length	910 nm
	pulse repetition rate	5 kHz
	pulse width	<10 ns
	pulse rise time	<1 ns
	opt. peak output power	5 W
	optical average output power	<0.3 mW (eye-safe)
	receiver diode	fast PIN diode
	receiver bandwidth	500 MHz
Scanner Control	Scanner Control Electronics	regulate and drive the torque motors by a closed loop PID control
	Scanner Control Interface	IF between MP and SCE eval. unit of the mirror rotary encoders
MicroProcessor	Digital Signal Processor	32/40-bit floating point device (ADSP 21020)
Data Bus Interface	MIL-STD-1553B Interfaces (original and redundant ones)	IF to GNC

Table 2 RVSE Main Parameters

3 Data Processing

The RVS Soft Ware (SW) is based on a modular concept. A number of operational Modes and Sub-Modes have been defined to cover the required functions: Initialisation and Configuration, SelfTest, Acquisition, Track, Stand-by. After receiving a Switch-On command, RVS performs an automatical initialisation and self test and switches to stand-by. A transition from stand-by into acquisition must be commanded. In case acquisition is performed successfully (i.e. RVS has acquired a target over more than one frame), RVS automatically goes into track mode. The actually selected sub-track mode - differences refer to the size of the scan window and to the modus of tracking the total TP respectively the retro reflectors sequentially - depends on the measured range value and the discriminatability of the of the retro reflectors of the TP. In case of target loss (for instance in case of leaving the specified approach corridor, see § 5), RVS automatically switches into acquisition mode and stays there up to reacquisition of the TP. For very short distances between Chaser and Target space craft (i.e. for R<10m), a Single Reflector Mode (SRM) was defined to cover the special conditions during the Flight Demos: Due to the size of the TP and due to a lateral displacement between RVSH and the centre of the TP at docking state, RVS can lose one of the Retros of the TP in case of keeping the nominal approach corridor for any range <10m. In case RVS would switch than into Acquisition Mode, no useful target information would be available down to docking. Switching into SRM, range and LOS values derived from the measurement results of the tracked single reflector are available down to loss of this retro by the actual geometrical conditions.

The RVS data output frequency is 2Hz.

Fig. 5 gives an overview over the main modes and the allowable mode transitions within RVS: „c" are allowable commanded transitions, „a" denotes automatical mode transitions.

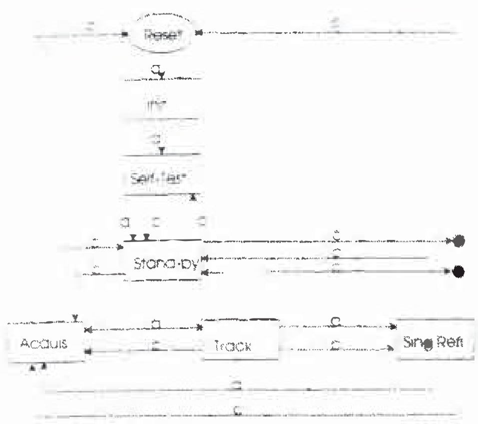


Fig. 5 RVS Main Modes and Mode Transitions

Table 3 summarises the main parameters of the operational modes.

Mode	SubMode	Mode / Sub-Mode Description
Init	-----	performs HW, SW, and IF's initialisation; successfully performed Init is shown during the first frame of Self-Test
Self-Test	-----	automatically after Init or commanded from Stand-by; results of the test are visible in form of BIT Error Flags
Stand-by	-----	automatical after Self-Test or commanded; electronics are powered and thermally controlled; no laser pulses
Acquisition		automatical in case of target loss at any range or loss of one or two retros for R≥10m, or commanded (AM0 only); duration depending on scan window size, RVS mode status and health status after each 0.5 sec frame;
	AM0	for first acquisition or for reacquisition in case of AM1 resp. AM2 was not successful, scan window: 30°x30° ... 12°x12°
	AM1	automatical for reacquisition in case of R≥60 m during target loss; automatical after AM0 in case of R≥60 m during target acquisition; scan window: 5°x5°
	AM2	automatical for reacquisition in case of R<60 m during target loss; automatical after AM0 in case of R<60 m during target acquisition; scan window: 5°x5 ... 20°x20°
Track		automatical after successful acquisition, valid attitude values in TM only
	TM1	down to 60m (approach) or starting from 55m (retreat) in case the three retros can not be separated by RVS, scan window: 1.5°x1.5° ... 3.0°x3.0°
	TM2	down to 60m or starting from 55m in case the three retros can be separated by RVS, three retros in one scan window, scan window: 1.5°x1.5° ... 3.0°x3.0
	TM3	between 60m resp. 55m and 40m, each retro in a single scan window; scan window: 1.8°x1.8°
	TM4	between 40m and SRM; valid R, LOS, and Attitude values
Single Reflector	SRM1, SRM2, SRM3	automatical in case of loss of one or two retros for R<10m, commanded from TM4, scan window: 1.8°x1.8°

Table 3 RVS Operational Modes

4 STS-84 Set-Up

The STS-84 mission was launched on 15 May 1997. Docking between Shuttle Atlantis and the MIR station was performed on 17 May, undocking on 21 May.

One of the payloads on the Shuttle was the European Proximity Sensor ARP-RVS. During this first RVS test in Space, the sensor was mounted on the Atlantis Docking Module next to the two American Trajectory Control Sensors (TCS), see Fig. 6. Before integration on Shuttle RVS had been verified on Earth and subjected to a Proto-Flight Qualification concerning Thermal Vacuum Loads, Mechanical Loads and EMC.

Table 4 gives the RVS performance results reached on static conditions at room temperature during the functional and performance test campaign on Earth :

at range = [m]		range accuracy [m]	azimuth, elevation accuracy [deg]	roll accuracy [deg]	pitch, yaw accuracy [deg]
1000 ... 100	bias	0.50			
	noise	0.22	0.25		
100 ... 40	bias	0.02	0.02		
	noise	0.08	0.08		
40 ... Rmin	bias	0.02	0.06	1.2 ... 0.3	1
	noise	0.05	0.07	6 ... 0.3	4 ... 2

Table 4 Performance test results under static conditions

In the docking and undocking phases both TCS and RVS were working. The TCS devices were guiding the Shuttle manoeuvres, RVS was running along with, delivering measurement data.

The retro reflectors of the RVS TP are mounted on the Docking Module which was delivered by Atlantis during the STS-74 mission (November 1994) and attached to the Kristall Module of the MIR Space Station. In order to avoid an in-flight interference between RVS and TCS, each RVS retro reflector is coated with an optical filter. As an additional but unintentional effect, these filters reduce the effective maximum range of the sensor to a value below 1,000 m.

During the Mission the RVS, TCS and further data files transmitted from Shuttle Atlantis to the Payload Control Centre on JSC could be watched. After the mission, the files were provided to DJO for further evaluation.

Before starting the RVS data evaluation, the available TCS1 and TCS2 data were subjected to a rough evaluation. Goal of this step was a selection of one of the TCS for comparison with RVS. Several non-regular behaviour of TCS1 (jumps to the RVS TP; earlier loss of the target than TCS2 before docking), led to a TCS2 selection for comparison with the RVS data files.

Fig 6 RVS covered with MLI (in the foreground) is mounted on the docking module of Shuttle Atlantis. Both TCS devices are visible in the background. The photo was taken after STS-84 mission before RVS disassembly for the check-out

5 In-Orbit Results

The evaluation of the data files available from the STS-84 mission led to the following results:

RVS worked in a stable moding during approach and retreat.

The sel●cted moding principle and the implemented moding structure have proved good during the mission. Moding simplifications are possible from the experiences gained during the flight demo.

RVS measured the following parameters during approach and retreat: range, azimuth, elevation, pitch, yaw, roll.

As specified, the attitude values pitch yaw and roll were valid for range < 40 m only. A comparison with TCS concerning these parameters can not be performed since TCS measures range and LOS only.

The achieved maximum range value of 754 m corresponds with the assessed Rmax values under the conditions of STS-84.

The maximum range value was achieved during retreat, RVS was tracking one of the NASA retros at this time. The loss of the RVS TP already at R≈400m results from a degradation of the retros, in particular of the optical filters during the time they were exposed to open space.

RVS Range, azimuth and elevation values correspond with the measurements of TCS.

All tendencies are correct, a numerical check performed at RVS minimum range delivered the expected values considering measurement and calculation accuracy.

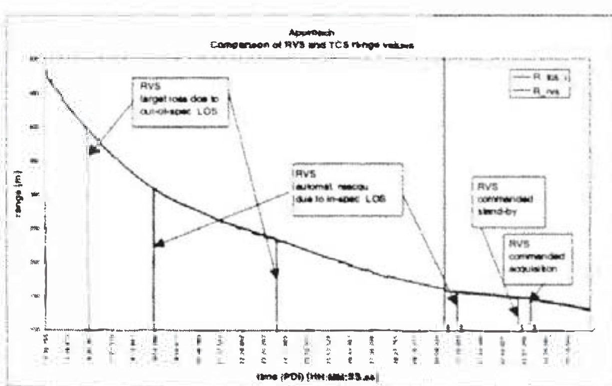
RVS HW and SW precautions protecting RVS from spurious reflections and NASA RR influences worked excellent.

During both approach and retreat, RVS did not track any active or passive light source than the RVS TP as long as the reflectivity of the RR's was sufficient. RVS switched to the NASA RR only, when the received reflected light of the ESA TP is too weak for pr●cessing on RVS. This RVS behaviour corresponds with what was implemented in the SW.

Meanwhile, RVS has successfully passed the second in-Space verification during the STS-86 mission. The data watched during the docking and undocking manoeuvres suggest a proper behaviour similar to those at the STS-84 mission.

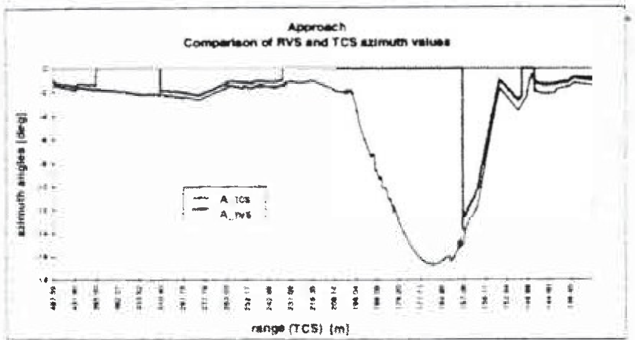
The following diagrams are selected from the enormous number of evaluation files of the STS-84 mission in order to demonstrate the RVS behaviour during approach and retreat. Comments to effects visible on the curves are given in the diagrams and in the column right of the curves.

The following 3 diagrams demonstrate TCS and RVS measurements between 480m and 140m.

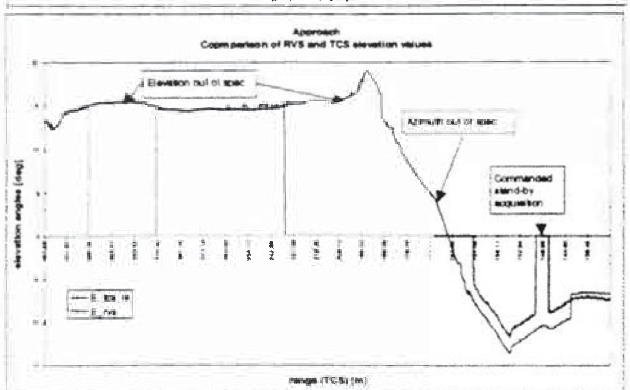


Between 48●m and 140m, RVS is in TM1 or - in case of target loss, see below - in Acquisition Mode.

RVS target loss between 400m and 310 m results from elevation values larger than +15 deg.

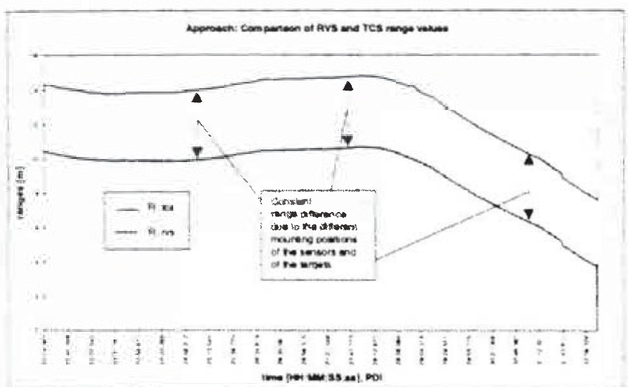


RVS re-acquires the target at R≈310 m, the elevation value is still close to +15 deg.
At R≈240m, the elevation angle between Shuttle and MIR is larger than +15deg again, reacquisition is possible after elevation *and* azimuth values are back in the specified ±15deg domain (R≈160m).

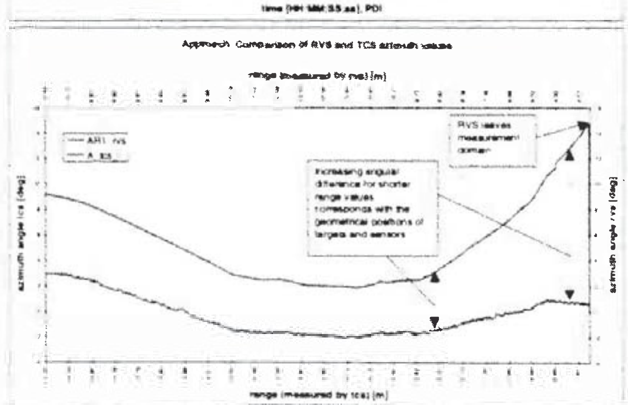


During station keeping at R≈150m a commanded reacquisition was performed after commanding stand-by.

The next 3 diagrams are derived from the measurements at R(RVS) = 10.5m ... 4m

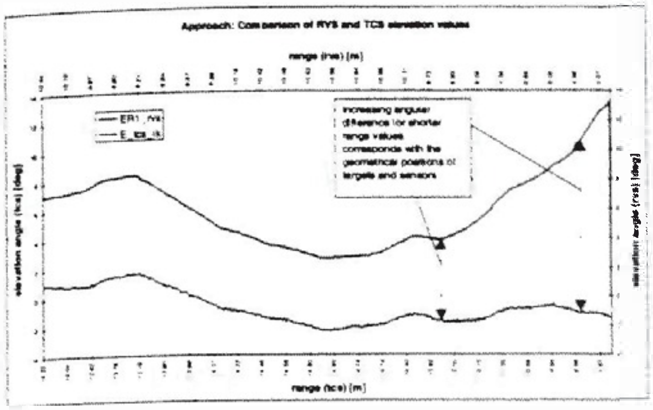


During the last station keeping before docking, RVS was commanded into Single Reflector Mode.



Due to the different retros tracked by RVS and TCS, and due to the different mounting positions of both the sensors, range, azimuth and elevation value of RVS and TCS are not identical.

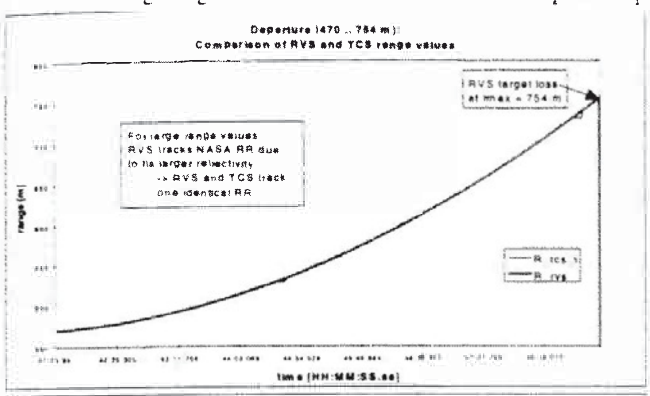
Resulting from the angular and range values measured at R(RVS)=4m and the

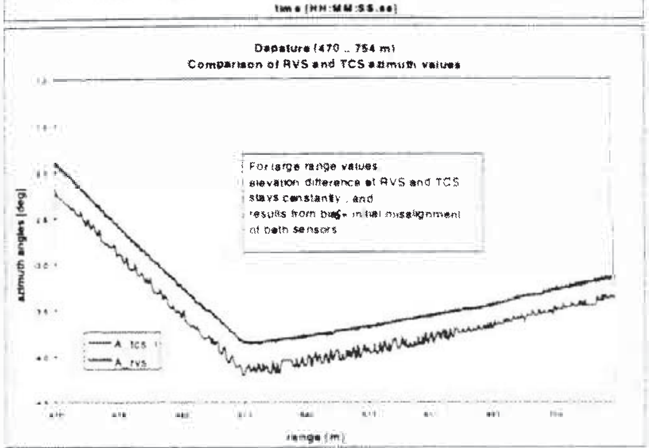


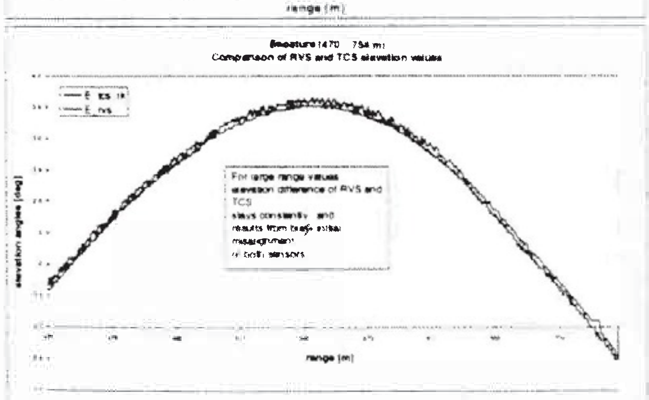
knowledge of the sensor and retro positions on Shuttle and on MIR, by mathematical means could be demonstrated that TCS2 (i.e. the NASA sensor selected for comparison with the RVS data) is equal to the one TCS mounted close to RVS (see Fig. 6)

At R= 4m, RVS lose the retro reflector due to an azimuth value of 15deg.

The following diagrams are taken from the retreat phase up to RVS retro loss at Rmax=754m







RVS is in TM1 again tracking the NASA retro (the same retro as TCS) due to the weak reflectivity of the RVS target.

6 Summary

A prototype of the Rendezvous and Docking Sensor RVS was successfully developed, manufactured, and verified on Earth and in Space during the ATV Rendezvous Predevelopment Project.

The sensor task to provide range, line-of-sight and attitude values during approach and retreat between a few hundred meters and docking is realised by a sensor concept of a scanning laser radar.

During two Flight Demonstration Missions (STS-84 and STS-86), RVS was delivering measurement data, while TCS was guiding the docking.

The evaluation of the data taken in-flight and during the test campaign on Earth demonstrate that

- RVS mastered a twice application in space without visible or measurable degradation including launches, landings, storage and handling in-between.
- the operational range of RVS fits to the requirement concerning short range guidance of an automatical docking and undocking manoeuvre
- the RVS moding concept is adequate to the tasks of the sensor. Moding stability during the track phase, automatical and commanded mode switching, for instance for re-acquisition are provided.
- the RVS measurement accuracy meets the requirements of an automatical docking. Range and LOS values correspond with the TCS measurements.
- the implemented HW and SW precautions, providing the ability to cope with spurious reflections and outer disturbances, worked excellent.

Thus, the results of the ARP-RVS prototype testing and application should be an good basis for the development of sensors for all task in the frame of high-accuracy navigation, rendezvous, berthing, and docking purposes especially to and from the International Space Station.

7 Acknowledgement

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