THE GNC MEASUREMENT SYSTEM

FOR THE AUTOMATED TRANSFER VEHICLE

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ABSTRACT

The Automated Transfer Vehicle (ATV) is a European Space Agency (ESA) funded spacecraft developed by EADS Space Transportation as prime contractor for the space segment together with major European industrial partners, in the frame of the International Space Station (ISS). Its mission objective is threefold : to supply the station with fret and propellant, to reboost ISS to a higher orbit and to dispose of waste from the station. The ATV first flight, called Jules Verne and planned on 2005, will be the first European Vehicle to perform an orbital rendezvous.

The GNC Measurement System (GMS) is the ATV on board function in charge of the measurement data collection and preconditioning for the navigation, guidance and control (GNC) algorithms. The GMS is made up of hardware which are the navigation sensors (with a certain level of hardware redundancy for each of them), and of an on-board software that manages, monitors and performs consistency checks to detect and isolate potential sensor failures. The GMS relies on six kinds of navigation sensors, used during various phases of the mission : the gyrometers assembly (GYRA), the accelerometers assembly (ACCA), the star trackers (STR), the GPS receivers, the telegoniometers (TGM) and the videometers (VDM), the last two being used for the final rendezvous phase. The GMS function is developed by EADS Space Transportation together with other industrial partners: EADS Astrium, EADS Sodern, Laben and Dasa Jena Optronik.

1. GENERAL PRESENTATION OF THE ATV

1.1 Mission Objectives

The Automated Transfer Vehicle (ATV) is a European unmanned, expandable logistic transportation system (20 tons class) for Low Earth Orbit. Its mission is to contribute to the logistic servicing of the International Space Station (ISS), that is:

- to supply the ISS with fret (crew items, scientific experiments, spare parts, …) and with water and gas,
- to retrieve the ISS waste and to burn them down during ATV re-entry in atmosphere,
- to provide a re-boost capability to the ISS, but also to contribute to the ISS attitude control when docked.

1.2 Description of the space vehicle

The ATV is composed of the following main three subassemblies:

- the Integrated Cargo Carrier (ICC) used to transport pressurised cargoes, fluids and gas, and to perform the re-fuelling of the ISS. It contains an equipped pressurised module and an active docking unit with its associated avionics system,
- the Equipped Avionics Bay (EAB) that accommodates the major part of the avionics equipment,
- the Equipped Propulsion Bay (EPB) that accommodates the propulsion and the re-boost system.

The EAB, the EPB and the separation and distancing module form the ATV spacecraft subassembly. The solar generation system is fixed on the EPB.

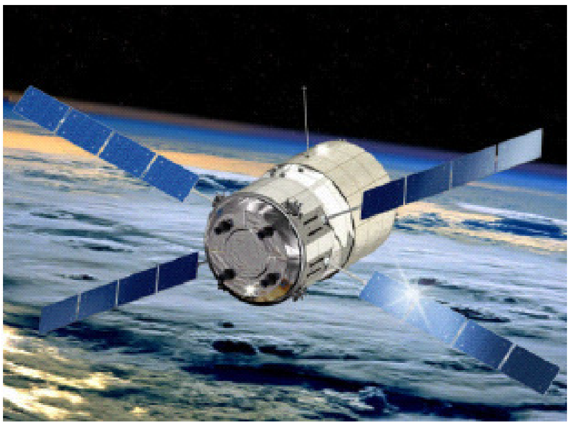

Fig. 1. ATV vehicle

1.3 Flight scenario

The nominal flight scenario is as follows: ATV is launched by Ariane 5; then, the flight sequences are separation, transfer to a phasing orbit, phasing with the ISS and rendezvous manoeuvres leading to the docking. The whole sequence can last up to three days in nominal case. After an attached phase (including ISS re-boost sequences) that can last up to six months, the end of the mission consists in departure from ISS, de-orbitation and atmospheric re-entry.

Some degraded phases or alternate mission plans are foreseen such as collision avoidance manoeuvre, in order to ensure the ISS proximity flight safety, or survival sequences.

2. GMS FUNCTION OVERVIEW

2.1 Objectives of the GMS function

The main purposes of the GNC Measurements System (GMS) are to provide the ATV with:

- the gyrometers assembly (GYRA) measured angular rate with respect to the inertial reference frame, in order to predict the ATV inertial attitude,
- the star tracker (STR) measurements of the ATV three-axis attitude with respect to the inertial reference frame, in order to update the ATV attitude prediction,
- the measurements of pseudo-range, pseudo-range rate and PVT for each GPS satellite observed, in order to estimate the ATV absolute position and velocity. These measurements also used to estimate ATV/ISS relative position and velocity and for monitoring,
- the videometer (VDM) measurements of range, LOS angles (azimuth and elevation) and relative attitude, in order to estimate the relative position, velocity and attitude between ATV and ISS,
- the telegoniometer (TGM) measurements of range, LOS angles (azimuth and elevation) in order to monitor the relative position and velocity between ATV and ISS,
- the accelerometers assembly (ACCA) velocity increments, in order to monitor the ATV boosts and the nominal state vector.

2.2 GMS functional breakdown

The GMS FU is divided in six independent sub-functions: GMS GYRA, GMS STR, GMS GPS, GMS TGM, GMS VDM and GMS ACCA. Each one is composed of hardware parts which are the sensors and software parts called Functional Unit Manager (FUM) which are in charge of:

- post-preocessing (e.g. computation of the angular rates from the gyros increments, calibration…) and projection of the measurements in a common inertial reference frame,
- low-level Failure Detection and Isolation (FDI) with equipment health-status,
- consistency checks with measurements when possible,
- management of the sensors configuration (warm-up, command of equipment internal modes…).

2.3 Interface between GMS and other functions

The GMS function is in interface with several ATV main functions, mainly: Mission and Vehicle Management (MVM), Guidance, Navigation and Control (GNC), Flight Control Monitoring (FCM) and Telemetry and Telecomands function (TMTC). The GMS provides the GNC and the FCM with the sensor measurements and an associated validity flag. It provides the MVM with alarms when a failure is detected or isolated. The MVM is in charge of the recovery.

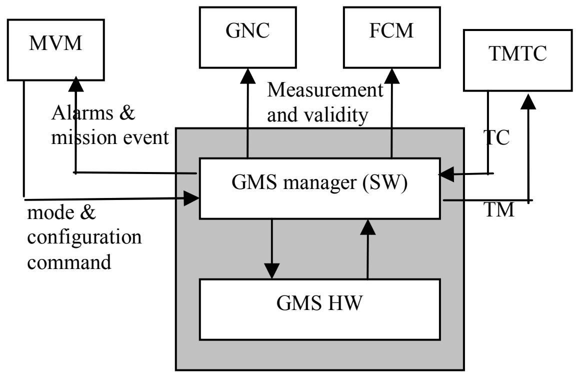

Fig. 2. GMS interfaces

2.4 GMS utilisation profile

The GMS utilisation profile is described in the following table:

Table 1. Sensors utilisation profile

Phase	**GYRA**	**STR**	**GPS**	**TGM**	**VDM**	**ACCA**
Launch	X					
Stabilisation	X	X	X			X
Phasing	X	X	X			X
Rendezvous	X	X	X	X	X	X
Attached						
Departure	X	X	X			X
Survival	X	X				

The GYRA and STR are used during the whole mission for the absolute attitude navigation. The STR can provide measurements until docking.

The GPS are used during phasing and departure for the absolute position navigation and during the far rendez-vous for the relative position navigation and for monitoring.
The TGM and VDM are used for the relative navigation and monitoring during the final approach.
The ACCA are used during the whole mission for the boost monitoring during phasing and for monitoring during rendez-vous.
The survival relies on the GYRA and STR for the navigation.
All the GMS and navigation processes are performed on-board except the absolute position navigation performed on ground.

3. THE GMS SENSORS

The hardware part of the GMS consists in six kinds of navigation sensors: a gyrometers assembly (GYRA), an accelerometers assembly (ACCA), two star trackers (STR), two GPS receivers, two telegoniometers (TGM) and two videometers (VDM).

3.1 GYRA

The GYRA provides the absolute attitude navigation with the angular rate measurements. It is developed by EADS Astrium and is composed of the following subassemblies:

- four identical two-axes Dynamically Tuned Gyros (DTG), each one is mounted on a shock isolator,
- one common baseplate supporting the four DTG,
- two gyro electronics units built-in with two identical and fully independent electronics channels. Each electronic channel contains the whole conditioning functions of the DTG.

The GYRA can operate in fine mode (for angular rates up to 2 deg/s) or in coarse mode (for angular rates up to 30 deg/s). It provides angular increments measurements at a rate of 10Hz after a 60 min warm-up.

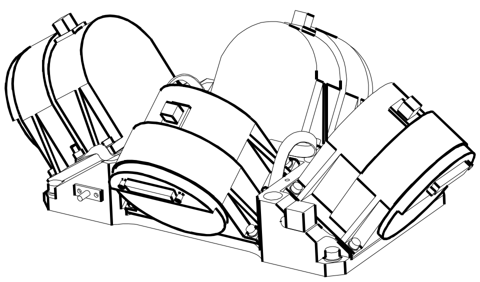

Fig. 3. GYRA mechanical part

Table 2. GYRA main performances

Specification	Fine mode	Coarse mode
Max. constant drift variation after in-flight calibration over 140 hours	1,5 deg/h	1,5 deg/h
Scale factor knowledge	10^{-3}	3.10^{-3}
Angular resolution	0,5 arcsec	20 arcsec
Angular noise (3σ) at 10Hz	3.10^{-3} deg	3.10^{-3} deg

3.2 STR

The STR allows the updates of the ATV inertial attitude and estimation of the GYRA drift. The STR performs the measurement of stars location and brightness in a two-dimensional frame, by the mean of a detector device (CCD matrix). It delivers three-axis attitude of a measurement reference frame in the J_{2000} reference frame. To do so, it uses a star catalogue and pattern recognition algorithms to acquire attitude, even in Lost in Space conditions. After the attitude acquisition, the STR can track the stars and deliver updated quaternions at a rate of 5Hz. It is developed by EADS Sodern.

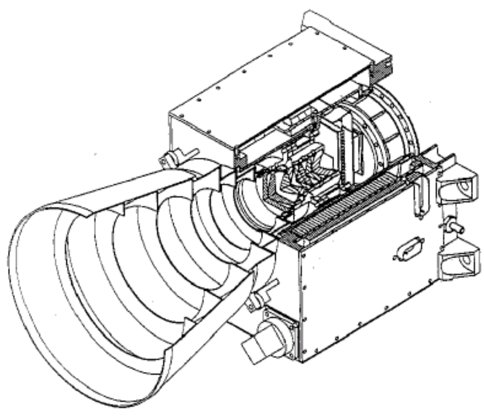

Fig. 4. STR mechanical part

Table 3. STR main performances

	Specification
Maximum angular rate	5 deg/s
Field of View	25 deg circular (± 12,5 deg)
Number of stars	From 3 up to 10
Bias errors (3σ)	10 arcsec (X,Y), 11 arcsec (Z)
Orbital and low frequency errors (3σ)	17 arcsec (X,Y), 84 arcsec (Z)
Noise Equivalent Angle (3σ)	27 arcsec (X,Y), 222 arcsec (Z)

3.3 GPS

The GPS, developed by Laben, is used to provide ATV with position, velocity and time (PVT) measurements. It is composed of two redundant chains, each one containing an antenna, a low noise amplifier and a receiver. It provides PVT at 1Hz with the following performances.

Table 5. GPS main performances

	Specification
Position (95%)	51m
Velocity (95%)	0,2 m/s
Time	1 µs
Pseudo-range (1σ)	5m
Pseudo-range rate (1σ)	0,03 m/s

3.4 VDM

The VDM developed by EADS Sodern is based on imaging sensor technology. A laser source is used to illuminate a rendezvous target on the service module. The resulting image produced on the VDM CCD is then processed in order to provide range, LOS angles and relative attitude during the last part of the final approach.
It is composed of:

- on-board ATV: two VDM, each one composed of one electronic unit and one optical head,
- on-board ISS: a rendezvous target composed of an inner target made of 5 single retro-reflectors and an outer target made of 3 multiple retro-reflectors (each multiple retro-reflector (MRR) is actually a cluster of seven single retro-reflectors).

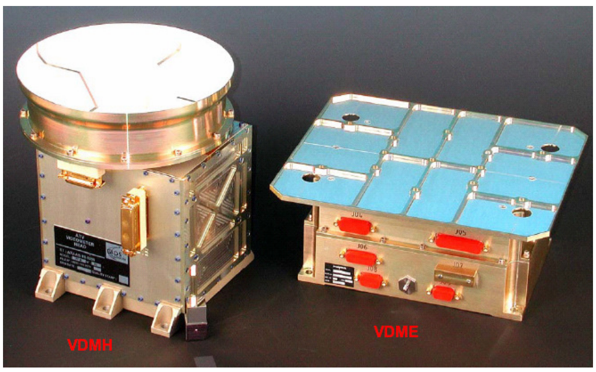

Fig. 5. VDM mechanical and electronic parts

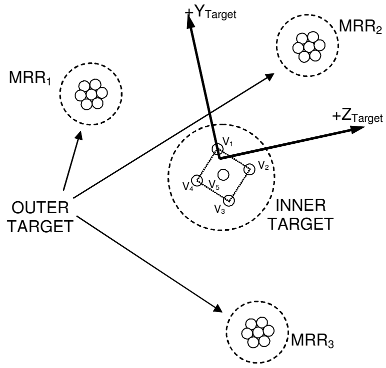

Fig. 6. Rendezvous target

Table 6. VDM main performances

	Specification
Range domain	1.25m<R<300m
LOS domain	± 8° at 300m
Range error	Bias: 3m, noise(3σ): 15m at 300m Bias<0.1m, noise(3σ)<0.1m for range<10m
LOS error	Bias : 0.3°, noise(3σ): 0.05° at 300m Bias<0.5°, noise(3σ)<0.05° for range<10m
Attitude error	Bias : 0.8°, noise(3σ): 0.1° at 20m

3.5 TGM

The telegoniometer delivers at 3Hz the range, the Line of Sight angles (azimuth and elevation). It is an active opto-electronic measurement system based on a laser range finder (measurement of the laser pulse time of flight). This rendez-vous sensor is developed by Dasa Jena Optronik.
It is composed of:

- on-board ATV: two TGM, each one composed of one electronic unit and one optical head,
- on-board ISS: the same rendezvous target as VDM; the TGM uses only the outer target.

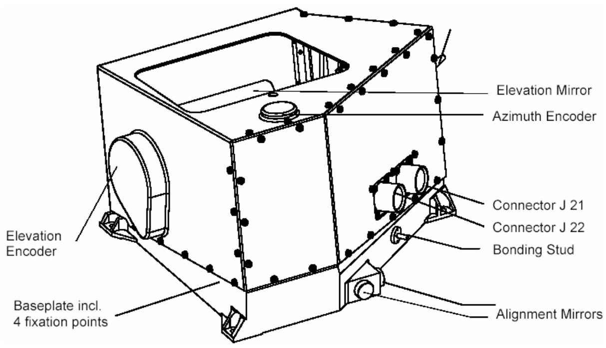

Fig. 7. TGM mechanical part

Table 7. TGM main performances

	Specification
Range domain	1.8m<R<700m
LOS domain	± 8° at 300m
Range error	Bias: 10.6m, noise(3σ): 9.8m at 300m Bias<0.2m, noise(3σ)<0.1m for range<10m
LOS error	Bias : 0.5°, noise(3σ): 0.2° at 300m Bias<1°, noise(3σ): 0.4° for range<15m

3.6 ACCA

The ACCA delivers the velocity measurements in order to monitor the ATV boosts. It is developed by EADS Astrium and is composed of the following subassemblies:

- six identical one-axis accelerometers,
- one common baseplate supporting the six accelerometers,
- three identical and independent electronic channels. Each electronic channel contains the whole conditioning functions for 2 accelerometers (which are named ACM).

The ACCA provides velocity increments measurements at a rate of 10Hz after a 10 min warm-up.

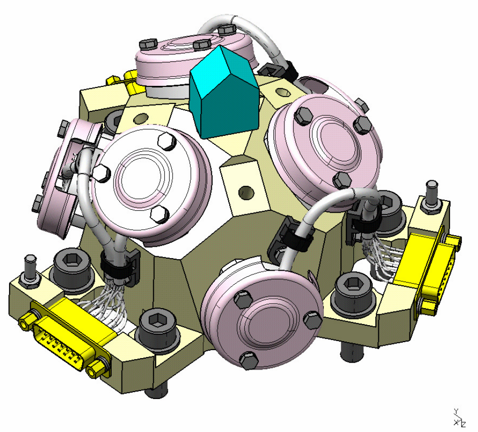

Fig. 8. ACCA mechanical part

Table 8. ACCA main performances

	Specification
Velocity pulse	1 mm/s
Maximum acceleration	0.1g in flight
In-orbit variation of the bias over 24 hours	< 50 µg
Scale factor knowledge	< 1000 ppm
Noise (at 1 Hz sampling)	< 1 mm/s

3.7 GMS avionics architecture

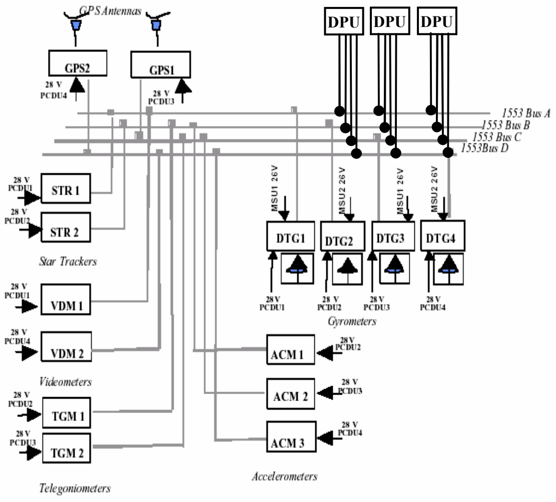

Fig. 9. Avionics architecture – GMS sensors

The hardware chains are organized in 4 lanes, each one having its own power distribution bus and a relevant 1553 data bus:

- Each sensor is connected to an independent power bus and an independent 1553 bus.
- Four Power Conditioning and Distribution Units (PCDU) provide power to the navigation sensors.
- Three Data Processing Units (DPU), which form a Fault Tolerant Computer (FTC) and contain the GMS manager, communicate with the sensors.

4. THE GMS MANAGER

The GMS manager has been developed by EADS Space Transportation and EADS Astrium. It is divided in six independent sub-functions: GYRA FUM, ACCA FUM, STR FUM, GPS FUM, TGM FUM and VDM FUM. Each FUM is built in the same way.

4.1 GMS modes and configurations

For each sub-function, some functional modes are defined as: the ON mode, OFF mode, survival modes. Within each mode, several configurations are defined: for example, in the GYRA ON mode, 11 configurations are defined; they represent all the possible configurations up to two GYRA failures. The current GYRA Finite State Machine (FSM) is then defined by one of these configurations: for instance, one GMS GYRA configuration is with 3 DTG healthy and one DTG failed.

The changes of modes and configurations are performed by the MVM according to the current state of the vehicle, the current phase, or alarms that can be raised by the GMS or other FU.

4.2 GMS services

Each FUM being built in the same way, the figure below given for GYRA is also applicable to other FUM.

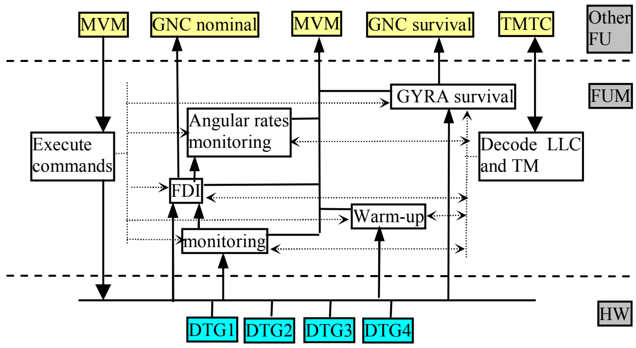

Fig. 10. GYRA FUM architecture

Each FUM is composed of the following services:

- Execute equipment commands: this process is in charge of the execution of the commands issued from the MVM and that can affect both the equipment and the other blocks of the FUM. MVM can send the mode or configuration commands defined above, or equipment commands, or software commands.
- Decode Low Level Commands (LLC) and perform Telemetry (TM): this process decodes the LLC coming from the TMTC FU and that can be used to modify some data (a threshold for instance) in the FUM. It also compiles all the TMs from the other blocks in order to send it to the TMTC FU.
- Monitor equipment parameters: this process is in charge of low-level tests; it consists in the monitoring of the equipment health status and the 1553 transfers. It raises an alarm to the MVM when a failure is detected. In that case, the MVM which is in charge the recovery, can send a configuration command.
- Monitor equipment warm-up: this process consists in managing and monitoring the warm-up of the equipment. This block can raise an alarm if the warm-up fails.
- Perform equipment Failure Detection and Isolation (FDI). This service is in charge of :
    - converting the sensor raw measurement into engineering data usable by the navigation algorithms,
    - checking equipment measurement validity,
    - performing FDI when possible using dedicated consistency tests and raising an alarm when a failure is detected.

  This block is the most complex one and is specific to each kind of sensor.
- Some other services are implemented for specific needs in each FUM as: monitoring of the angular rates for the GYRA, bias estimation for ACCA, GYRA survival, STR survival.

4.3 Failure Detection and Isolation (FDI) algorithms

For each kind of sensor, a dedicated FDI algorithm is implemented; this is due to the fact that the sensors do not deliver the same failure coverage through their health status and that they are not managed in the same way: GYRA and ACCA are in hot redundancy; GPS, TGM and VDM are used in hot redundancy at GMS level and STR is managed in cold redundancy. The consistency checks in the FDI algorithm are enabled only if the upstream monitoring of the equipment health status has been declared successful.

The GYRA FDI algorithm is based on a mixed solution of a 6-equation consistency method and a 24-equation consistency method. A consistency equation consists in a linear combination of the gyrometers measurements, which compared with a defined threshold, allows to detect and to isolate a failed gyrometer. This solution allows isolating two failed gyrometers with the required performance.

The ACCA FDI algorithm is based on a 3-equation consistency method. It consists in a linear combination of the accelerometers measurements, which compared with a defined threshold, allows detecting up to a second accelerometer failure.

The GPS FDI is based on low-level monitoring, on evolution consistency tests on code phase and carrier phase for each receiver and on consistency tests on code phase and carrier phase between the two receivers.

For the TGM FDI, one consistency check between the measured ranges of each TGM is performed.

For the VDM FDI, the same principle as the TGM is applied.

No consistency check is performed on the STR as they are managed in cold redundancy. The FDI is insured by the low-level monitoring.

5. CONCLUDING REMARKS

This paper presents the GMS function for the Automated Transfer Vehicle before the System Qualification Review. At this state, almost all the equipments qualification reviews have been performed.

6. ACKNOWLEDGEMENTS

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