TERMINALS AND MECHANISMS FOR OPTICAL COMMUNICATION

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ABSTRACT

In the near future, satellite networks will be an essential part of the upcoming Global Information Infrastructure. Several proposed satellite systems will employ optical inter-satellite links to network the satellites. The performance of the whole network is then dependent on the performance of the inter-satellite links to the other satellites. The high data rate requirements (1 GBit/s to 10 GBit/s) cannot efficiently be covered by RF-terminals. Optical links which use laser light as a carrier can transmit much higher data rates. Contraves Space recognised the demand for high data rate crosslinks and started the development of optical terminals in 1995 with support of ESA.

This paper focuses on the activities carried out in order to develop the Short Range Optical Inter-satellite Link Demonstrator terminal (SROIL-DM). It presents a description of the mechanism, identifying the most critical requirements that were to be met from the mechanical and structural point of view. The philosophy followed during the optimisation process is pointed out and the relevant modelling aspects will be discussed in order to clarify the results of the dynamic correlation performed between the finite element model and the data measured during a test campaign.

1. INTRODUCTION

The satellite networks that are designed for broadband data usually link several satellites within one constellation or even satellites of different networks. The most advantageous way to do this is to use the inter-satellite link directly, allowing the data to be routed from one satellite to another.

The performance of the satellite networks depends on the crosslink data rate and on the technology used to implement such a crosslink. In the past, the only available technical solution was represented by microwave links. This is the solution adopted for the interconnection between the 66 satellites of the IRIDIUM constellation. The next generation of inter-satellite-links and the next step in the evolution of satellite communication technology will be represented by optical links, that use laser light as carrier. The major advantage of optical links is the possibility to transmit much higher data rates.

Optical terminals can be used in different kind of applications: for space-to-ground links, for LEO, MEO and GEO satellite networks, as well as for location of satellites on highly elliptic orbits. Different applications mean different requirements for the lasercomm terminal. Two main aspects have to be considered when choosing the terminal for a specific application: the data rate to be transmitted and the network topology that determines the link range, the angular convergence, the dynamic behaviour of the terminal when it tracks the counter terminal.

In general a great difference exists between LEO and GEO satellite networks concerning the amount of data that has to be crosslinked. Due to the orbital position, LEO satellite networks are very dynamic and the GEO ones are much more static: therefore in the first case the system performance depends significantly on the performance of the inter-satellite-links and on the way the traffic is routed. In this second case, only a certain percentage of traffic goes to adjacent satellites. Data rates that are currently being discussed range from several 100 Mbps up to 6 Gbps, and data rate requirements up to 10 Gbps are to be expected soon.

In order to provide data rates up of several Gigabits per second, with only a few Watts of power, extremely narrow laser beams are used. For the beam pointing mechanism this means that the pointing stability of the beam has to be maintained within a few microrads. It is also necessary to precisely point the outgoing beam slightly into another direction than the incoming one, to account for the finite velocity of the light.

In view of these stringent requirements, even small disturbances produce undesired effects on the link stability. Mechanical disturbances due to the spacecraft, secondary effects of actuators within the terminal and eventually, thermoelastic effects require a dedicated consideration.

The network topology defines the inter-satellite-link distance: for LEO and MEO applications short/medium distances are foreseen (1000 up to 15000 km) and for the GEO the link distance come up to 80000 km.

In order to define a full set of characteristics for the lasercomm terminals, some additional aspects have to be considered:

- Sun interference immunity, that means the possibility to operate with the sun in the terminal field of view;
- Power consumption, mass, volume ease of accommodation on the host spacecraft;
- Acquisition time;
- Costs for the satellite integration (integration environment, alignment and test procedures);

- Reliability, lifetime, availability (in-orbit alignment and optimisation procedures)
- Uninterrupted communication service, that means that the link must not be interrupted nor disabled by periodically disturbances.

According to the above mentioned aspects and including the requirements for very low mass, volume and power consumption, Contraves Space Zurich started in 1995 the development of a Short Range Optical Inter-satellite Link (SROIL) terminal. A SROIL Demonstrator (DM) has been built and successfully tested in 1997. A medium range terminal has been designed in 1998 and, to complete this family of terminals, one for long-range application is currently under development. All these developments are been performed with the support of the ESA.

2. TERMINAL DESCRIPTION

The SROIL-DM terminal consists of three main structural sub-units, shown in Figure 2.1. These sub-units are:

- Support Unit: it forms the carrying structure of the terminal.
- Compound Pointing Assembly: it is mounted on the top of the housing and it performs the coarse line of sight control. It can perform beam steering in the terminal azimuth as well as in the elevation direction. It consists of the following critical components:
  - Azimuth Scan Unit: azimuth drive unit, bearings and encoder
  - Elevation Scan Unit: elevation drive unit, bearings and encoder
  - Cable Drum Assembly: which contains the cable for the elevation motor drive and the optic fibre from the two beacon laser collimators mounted on the elevation unit.
  - Light Conductor Drum Assembly: which contains the optical fibres for the two beacon collimators mounted on the elevation unit.
- Optical Bench: this is the carrying structure for the optical elements. Both the acquisition and transmitter optical path are inside that sub-unit. In addition, it carries the following sensors and actuators:
  - Acquisition sensor (AS).
  - Tracking sensor (TS).
  - Point ahead sensor (PAS).
  - Fine pointing assembly (FPA).
  - Point ahead assembly (PAA).

The overall dimensions of the terminal are 260 mm width, 200 mm length, 430 mm height.

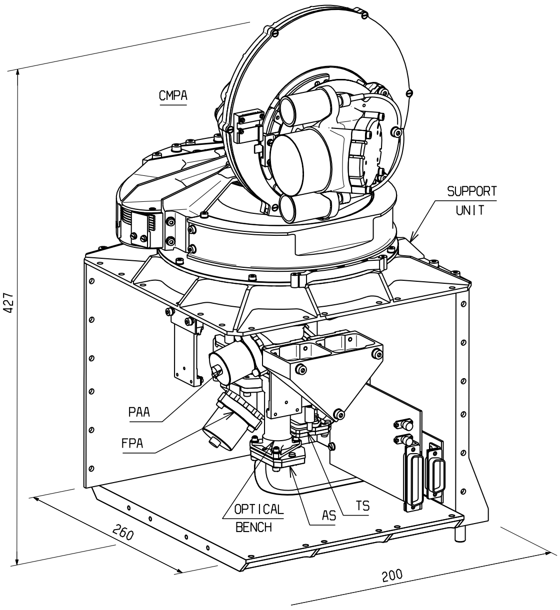


Figure 2.1. SROIL-DM Terminal.

3. MECHANICAL SPECIFICATION

The criticality of the mechanical requirements is due to fact that the laser beam pointing stability must be maintained in a very narrow range. At the same time, the structure must be light, has to provide sufficient strength and stiffness in order to withstand the launch environment and to minimise the effect of external microvibrations on the optical performance.

As a consequence, the requirements important for the design are:

- Mass: the mass for the whole SROIL-DM terminal cannot exceed 10 kg.
- Minimum stiffness: specified as the minimum eigenfrequency to be met. Being the goal to achieve a minimum coupled eigenfrequency of 150 Hz for the entire structure of the terminal, a minimum individual eigenfrequency of at least 200 Hz is required for each one of the three sub-units.
- Minimum strength, specified as a set of load conditions and factors of safety to be applied. In particular, in order to take into account all potential launch vehicles a quasi-static load is used for the initial sizing of the components. It is given by the following formula:

$$a = \frac{190}{\sqrt{m}}$$

with “a” being the resulting acceleration in [g] and “m” the effective mass in [kg] of the component under consideration.

- Maximum distortions specified as maximum tolerated angular misalignment between related axes and line of sights. The thermal distortions are the most important source of misalignment within the structure and the allowed value for the light of sight inside the optical bench are in order of few tens of µrad. . The other source of misalignment is the microvibration external environment. In this case the requirement are even more stringent than the values specified for the thermal distortions.

4. STRUCTURE OPTIMISATIONS

As already mentioned, the essential requirement for the structure of such a mechanism is to provide the correct angular alignment between the various optical units to maintain the line of sight stability. But this is only one of the specifications that have to be met: mass, stiffness and strength play a role which is equally important. This means that the optimum has to be found between requirements which sometimes are also conflicting. The following points will explain the structure optimisation philosophy:

- All rotating components shall be statically balanced such that translation disturbances do not lead to rotational distortions of the optical components. The balancing requirement usually does not impose any particular difficulty with respect to the terminal design.
- The support unit compliance of the load path to the spacecraft shall be maximised to reduce the high frequency disturbances (low pass filter).
- On the other hand a sufficiently high stiffness within the structure must be present to decouple the terminal modes from important spacecraft modes in order to maintain the launch loads within reasonable values.
- Sufficiently high structural strength to survive the launch environment.
- The design allows for a highly modular system. This is mainly for two reasons: the wide number of possible mission scenarios for the terminal application and the necessity of mass production. This last is in particular true for the application on LEO constellations as they consist of up to hundreds of satellites with typically 4~6 terminals per spacecraft.
- To reduce complexity.
- An appropriate selection of materials: aluminium is used for the Optical Bench because of its high λ/α ratio in order to minimise the thermal gradients and distortions.
- An appropriate configuration has been selected in order to minimise the temperature gradients across the optical unit. Such gradients lead to bending of the telescopes which implies an angular misalignment. In Figure 4.1 the solution adopted to attach the part supporting the tracking sensor (high dissipative item) to the acquisition tube is presented.
- The optical bench is as a thin walled precision casting structure. Due to the complex shape of the bench resulting from the optimisation process, casting is the optimum manufacturing procedure to leave the material only where it is functionally needed, reducing the global mass.

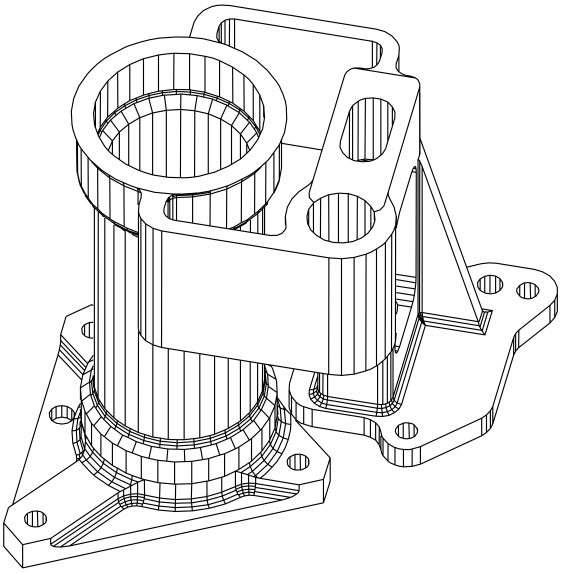


Figure 4.1. Fixation of the tracking sensor unit to the acquisition tube.

5. MODELLING ASPECTS

The finite element model prepared for the terminal follows the mechanical sub-units breakdown. Therefore three main models have been prepared: one for the CMPA, one for the Optical Bench and one for the Support Unit. The complete model of the system has been created by combining the three models.

A high detailed model was generated because of the complexity of the system and the very accurate evaluation required for the dynamic behaviour until the sensors level and for the thermoelastic distortions.
The calculations have been carried out with NASTRAN.

The complete FE model is shown in Figure 5.1. In this figure the model of the optical bench inside the support unit is represented only by few lines. That is because that model was condensed for limiting computational time.

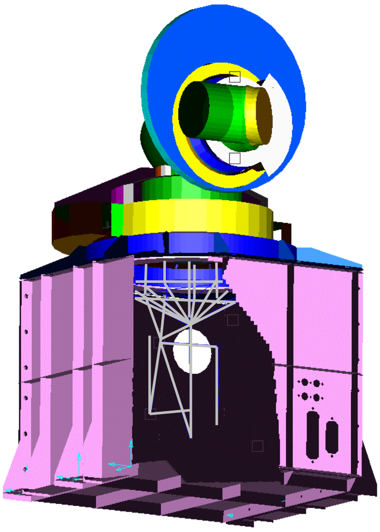


Figure 5.1. SROIL-DM complete finite element model

6. MEASUREMENTS AND DYNAMIC CORRELATION

Once the terminal has been manufactured and assembled, it has been possible to measure the real dynamic behavior of the structure. A campaign of measurements was carried out and the data have been used to correlate the dynamics of the SROIL-DM terminal and the analytical results. Consequently, remaining discrepancies between the FE model and the terminal structure were pointed out and modifications implemented in the model in order to assure it is representative of the reality.

6.1 Measurements

The measurements were performed mounting the SROIL-DM Terminal on a vibration jig as shown in Figure 6.1, and exciting the plate where the terminal is fixed in three directions. Accelerations were collected at 38 locations of the mechanism. In order to excite the fundamental resonance of the structure and to collect information to accurately describe its dynamic behavior, the position of the accelerometers and of the shaker were chosen on the base of the analytical mode shapes. The measurements were performed with the two motors controlled with a stiffness below 5 Hz to avoid coupling with the dynamics of the system.

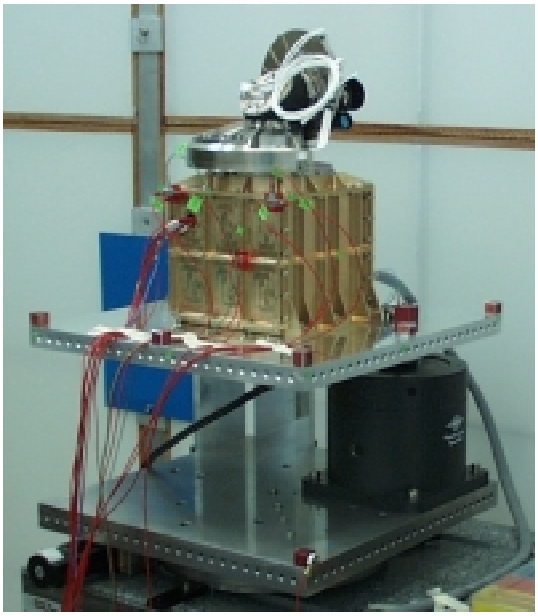


Figure 6.1. Measurements configuration.

6.2 Dynamic Correlation

The correlation required the estimation of the modal parameters of the structure (resonance frequencies, damping and mode shapes) from the collected data [1]. Once this information was available a mathematical model of the vibrational properties and the behavior of the tested structure was built and compared with the finite element model.

The data measured was in the form of frequency response functions, that means they represented the ratio between the response acceleration at a point and the exciting force. From this data, condensed into a transfer function matrix, employing a multi degree of freedom technique [2], the resonance frequencies and the associated damping were identified on the basis of the best interpolation of the measured FRFs and of a Modal Confidance Factor close to 1. Then, the modal parameter table was completed computing the residues, amplitude and phase, for each resonance. Thereafter the mode shapes could be estimated.

Before using this modal model for the correlation with the FE model, it has been validated by:

- Synthesizing the frequency response functions, in order to compare those ones based on the modal model and the measured ones;
- Calculating the modal assurance criteria matrix between the modal model and itself, in order to verify the presence of double eigenmodes due to a redundant selection of the modal parameters.

At the end, the MAC Matrix has been generated comparing the mode shapes calculated by the FE model and the modes extracted from the modal model. In order to improve the correlation, some modifications were brought in the FE model, consisting in more appropriate material properties and detailing the modeling of some parts, like bearings.

The aim of the dynamic correlation was to validate the quality of the FE model because this was required to derive the structural behavior influencing the controllability of the mechanism.

The resonance frequencies of the SROIL-DM mechanism are within the bandwidth of the control system, therefore an interference between structure and controller could not a priori be excluded.

The control consists of two loops:

- The CMPA loop which operates in the low frequencies range, up to 80 Hz;
- The FPA loop, which operates in the high frequencies range, above 200 Hz.

It is important therefore that the response of the FE model in these two ranges of frequencies is representative of the real behavior of the structure.

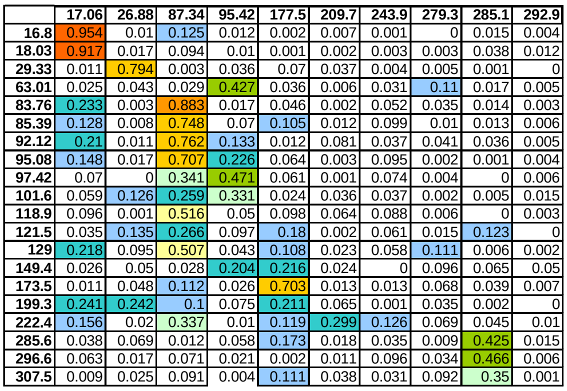
From the structural point of view, the dynamics in the above mentioned ranges, is characterized by:

- low frequencies range (up to 80 Hz) driven by the vibration jig which simulates the spacecraft dynamics;
- intermediate frequencies range (80-250 Hz), the CMPA components behavior and parameters, as the real stiffness of the bearing, are dominant;
- high frequencies range (> 250 Hz) driven by local units, as the optical bench.

From the MAC matrix shown in Figure 6.2, results that:

- An excellent correlation exists for the modes in the low frequencies (MAC greater 0.8)
- The dynamics in the medium range of frequencies is only roughly representative;
- The mode driven from the optical bench, at around 300 Hz, results well correlated taking into account that is a local mode.

The FE model has been proved to be perfectly suitable for our purpose.



	17.06	**26.88**	**87.34**	**95.42**	**177.5**	**209.7**	**243.9**	**279.3**	**285.1**	**292.9**
16.8	0.954	0.01	0.125	0.012	0.002	0.007	0.001	0	0.015	0.004
18.03	0.917	0.017	0.094	0.01	0.001	0.002	0.003	0.003	0.038	0.012
29.33	0.011	0.794	0.003	0.036	0.07	0.037	0.004	0.005	0.001	0
63.01	0.025	0.043	0.029	0.427	0.036	0.006	0.031	0.11	0.017	0.005
83.76	0.233	0.003	0.883	0.017	0.046	0.002	0.052	0.035	0.014	0.003
85.39	0.128	0.008	0.748	0.07	0.105	0.012	0.099	0.01	0.013	0.006
92.12	0.21	0.011	0.762	0.133	0.012	0.081	0.037	0.041	0.036	0.005
95.08	0.148	0.017	0.707	0.226	0.064	0.003	0.095	0.002	0.001	0.004
97.42	0.07	0	0.341	0.471	0.061	0.001	0.074	0.004	0	0.006
101.6	0.059	0.126	0.259	0.331	0.024	0.036	0.037	0.002	0.005	0.015
118.9	0.096	0.001	0.516	0.05	0.098	0.064	0.088	0.006	0	0.003
121.5	0.035	0.135	0.266	0.097	0.18	0.002	0.061	0.015	0.123	0
129	0.218	0.095	0.507	0.043	0.108	0.023	0.058	0.111	0.006	0.002
149.4	0.026	0.05	0.028	0.204	0.216	0.024	0	0.096	0.065	0.05
173.5	0.011	0.048	0.112	0.026	0.703	0.013	0.013	0.068	0.039	0.007
199.3	0.241	0.242	0.1	0.075	0.211	0.065	0.001	0.035	0.002	0
222.4	0.156	0.02	0.337	0.01	0.119	0.299	0.126	0.069	0.045	0.01
285.6	0.038	0.069	0.012	0.058	0.173	0.018	0.035	0.009	0.425	0.015
296.6	0.063	0.017	0.071	0.021	0.002	0.011	0.096	0.034	0.466	0.006
307.5	0.009	0.025	0.091	0.004	0.111	0.038	0.031	0.092	0.35	0.001

Figure 6.2. Modal Assurance Criteria matrix between measured data (vertical) and analytical results (horizontal) .

7. CONCLUSIONS

This paper presented the steps relevant for the development of the SROIL-DM terminal, from the structural point of view. The severe requirements to be fulfilled have determined the design philosophy, in order to achieve the performance and the needed reliability on the analytical results. Structural optimisation and validation of the mathematical model used to verify the performance are the two key points that characterised this project. At the end a finite element model of the mechanism, suitable for both the thermo-mechanical calculations and for deriving the information required for controllability purpose, was available.

8. ACKNOWLEDGMENTS

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9. ACRONYMS

AS	Acquisition Sensor
α	Coefficient of thermal expansion
CMPA	Compound Pointing Assembly
CSZ	Contraves Space Zürich
FE	Finite Element
FPA	Fine Pointing Assembly
FRF	Frequency Response Function
GEO	Geostationary Earth Orbit
LEO	Low Earth Orbit
λ	Thermal conductivity
MAC	Modal Assurance Criteria
MEO	Medium Earth Orbit

PAA	Pointing Ahead Assembly
PAS	Pointing Ahead Sensor
SROIL-DM	Short range Inter-satellite Link Demonstrator
TS	Tracking Sensor

9. REFERENCES

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