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THERMAL/VACUUM MEASUREMENTS OF THE HERSCHEL SPACE TELESCOPE BY CLOSE-RANGE PHOTOGRAMMETRY

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ABSTRACT

In the frame of the development of a videogrammetric system to be used in thermal vacuum chambers at the European Space Research and Technology Centre (ESTEC) and other sites across Europe, the design of a network using micro-cameras was specified by the European Space agency (ESA)-ESTEC. The selected test set-up is the photogrammetric test of the Herschel Satellite Flight Model in the ESTEC Large Space Simulator. The photogrammetric system will be used to verify the Herschel Telescope alignment and Telescope positioning with respect to the Cryostat Vacuum Vessel (CVV) inside the Large Space Simulator during Thermal-Vacuum/Thermal-Balance test phases. We designed a close-range photogrammetric network by heuristic simulation and a videogrammetric system with an overall accuracy of 1:100,000. A semi-automated image acquisition system, which is able to work at low temperatures (-170°C) in order to acquire images according to the designed network has been constructed by ESA-ESTEC. In this paper we will present the videogrammetric system and sub-systems and the results of real measurements with a representative setup similar to the set-up of Herschel spacecraft which was realized in ESTEC Test Centre.

1 INTRODUCTION

Herschel is the fourth cornerstone mission in the European Space Agency's (ESA) science program. It will perform imaging photometry and spectroscopy in the far infrared and sub-millimeter part of the spectrum, covering approximately the 57-670 μm range and thus bridging the traditional space infrared range with the ground based capabilities. The key science objectives emphasize current questions connected to the formation and evolution of galaxies and stars and stellar systems, however, having unique capabilities in several ways, it will be a facility available to the entire astronomical community. Herschel's primary objectives are to:

- study the formation of galaxies in the early universe and their subsequent evolution
- investigate the creation of stars and their interaction with the interstellar medium
- observe the chemical composition of the atmospheres and surfaces of comets, planets and satellites
- examine the molecular chemistry of the universe

Herschel (Fig. 1) will be equipped with a passively cooled 3.5 meter diameter classical Cassegrain telescope. The science payload complement (two cameras/medium resolution spectrometers: PACS and SPIRE) and a very high resolution heterodyne spectrometer will be housed in a superfluid helium cryostat. The Herschel science payload comprises three instruments that perform a combination of spectrometry, imaging spectrometry and imaging photometry covering a wavelength range from 57 to 670 μm. The ground segment will be jointly developed by ESA, the three instrument consortia and NASA/IPAC.

Herschel will be carried into space from the Guiana Space Centre, Kourou, French Guiana by an Ariane 5 launcher. It will be launched together with ESA's Planck spacecraft. The two spacecrafts will separate shortly after launch and proceed independently to different orbits about the second Lagrange point of the Earth-Sun system (L2). Once operational about half a year after launch, Herschel will offer 3 years of routine observations. Approximately 2/3 of the available observing time is open to the general astronomical community through a standard competitive proposal procedure.

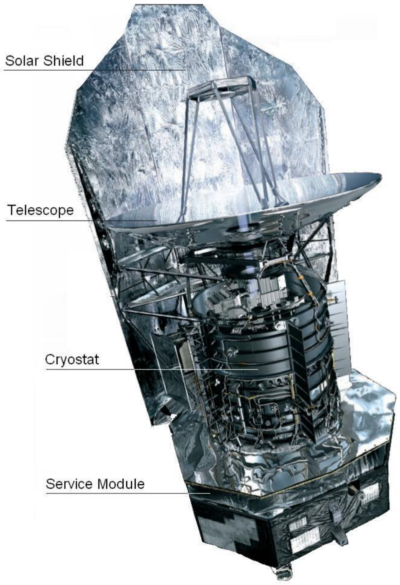


Fig. 1. Herschel space telescope and its components.

One of the factors which influence the quality of the imaging is alignment of the telescope. Real alignment of Herschel requires the measurements of the complete Flight Model and deformation monitoring in vacuum and at cryo-temperatures, which simulates the operational condition of the spacecraft in space. Two main measurement systems will be used in thermal/vacuum:

- the Heterodyne Instrument for the Far Infrared (HIFI) Alignment Camera System (HACS) is an Optical Ground Support Equipment that is specifically developed to verify proper alignment of different modules of the HIFI instrument,
- the videogrammetry System is a Ground Support Equipment that will be used to measure translations and rotations between the Locator Oscillator Unit and the Telescope. The videogrammetric measurements will be compared with the thermo-elastic Finite Element models predictions in order to increase the confidence of the alignment budget [5].

A thermal/vacuum qualified videogrammetric system has been constructed by ESA-ESTEC Test Centre Division. The construction follows a photogrammetric network based on an hyper redundant image acquisition concept. The design considers the mechanical and electronical implementation issues related to vacuum and cryo-temperatures (-170°C). Several tests were performed aiming at qualifying the videogrammetric system in terms of operation in vacuum, cryo-temperatures and accuracy. In terms of operation, the system was validated in vacuum and cryo-temperature conditions. In terms of accuracy budget the following were investigated and analyzed:

- the geometrical and radiometrical quality of the targets
- the accuracy of the sensors
- the potential accuracy of the videogrammetric network and the possibility of the on-the-job partial self-calibration of the cameras

A real test of a dummy object by the videogrammetric system aiming at the validation of the strategy for the measurement of the Herschel spacecraft was performed.

2 A THERMAL/VACUUM QUALIFIED VIDEOGRAMMETRY SYSTEM

ESA-ESTEC specified a videogrammetric system to be used in thermal/vacuum environmental conditions particularly for the measurement of the large space structures. The initial network design [3] was more focused on the photogrammetric requirements than the practical implementation issues of the designed network especially in vacuum and at cryo-temperatures. After some iterations, necessary modifications were made by ESA-ESTEC to match the designed videogrammetric network with practical implementations. Consequently photogrammetric simulations were carried out [4] in order to check the feasibility before the construction of the system and to estimate the measurement accuracy. This section summarizes the current status of the videogrammetric system.

The videogrammetric system is based on two identical and independent structures, which enables establishing a videogrammetric network for the measurement of large test specimens especially when the test specimen is constrained to be fixed during measurements. The operation of each structure is semi-automated and controlled by an operator. Each structure, independent from each other, includes two cameras with ring flashes. The videogrammetric network is configured by the translation of cameras and camera rotations toward the test specimen. This mechanism enables establishing a convergent videogrammetric network with a large base between cameras. Since the system works based on vertical scanning of the test specimen, a hyper-image photogrammetric network can be established. The videogrammetric system consists of different components: sensor, flash, mechanical structure and electronical system. The following sections describe the components.

2.1 Sensor and Optics

The sensor that we use for the videogrammetric system is a digital 1-mega-pixel space qualified camera (Fig. 2a) which has been developed by *Micro-Cameras and Space Exploration SA* for ESA's space missions. It is a compact and light-weight camera which is able to operate in harsh environmental conditions. It is able to work in vacuum and at a temperature down to -120°C without using any canister. With the built in internal heater the sensor is able to work at lower environmental temperatures too.

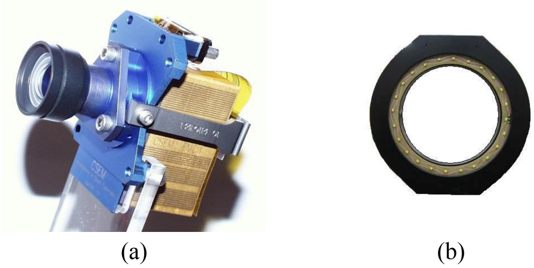

(a) (b)

Fig. 2. Digital space micro-camera. a) camera with optics and b) micro-LED's ring flash.

The optics of the micro-camera has a focal length of approximately 12.5 mm and considering the CCD-chip size the field of view is about 78° along the diagonal of the CCD. The aperture of the optics is fixed and is equal to f/10. The Modulation Transfer Function (MTF) of the optics is greater than 50% at 35 lines/mm. The band pass of the optics is approximately between 480 nm and 940 nm.

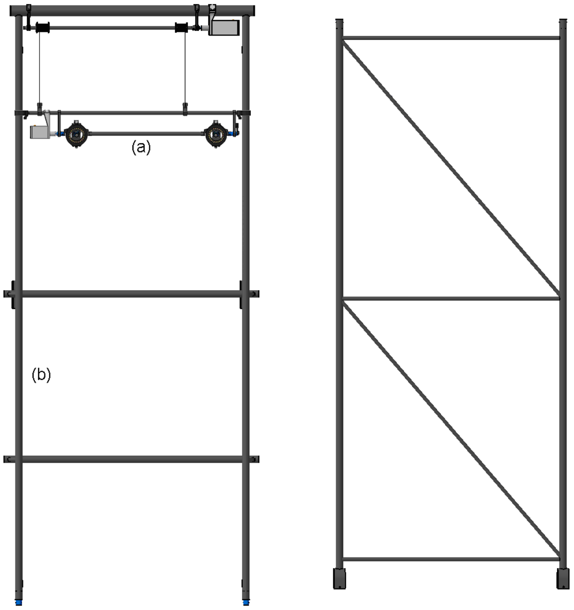
2.2 Flash

A micro-LED's ring flash (Fig. 2b) is used with a micro-camera [2]. Micro-LED's flashes have more reliability and maintainability with respect to tube flashes. In addition, they are able to operate in vacuum and at temperatures down to -180 °C (without canister and thermal protections) therefore no hot spot for the specimen is created by the flash except during the operational time required for the image acquisition. When a LED flash is on, given the duration of the light pulse of 100ms, the transmitting energy is 16J.

2.3 Mechanical Structure

The current videogrammetric system consists of two mechanical structures. Each mechanical structure consists of three parts:

- a movable structure which holds two micro-cameras with flashes (Fig. 3a),
- a main structure which holds the movable structure and guide the vertical sliding of the movable structure (Fig. 3a),
- a support structure which is used to elevate the rest of the system (Fig. 3c).



(a) and (b) (c)

Fig. 3. Components of the videogrammetric system. a) The movable structure with two micro-cameras and flashes, b) the main structure and c) the support structure.

The videogrammetric network is configured by a vertical translation and rotations of the camera around vertical and horizontal axes. A vertical translation and the rotation around the horizontal axis are actuated by means of stepper motors and can be remotely controlled during the test operation. The rotation of the cameras around vertical axis is set manually before the test and is fixed during the whole test campaign.

The mechanical structure is mainly made of Carbon Fiber Reinforced Plastic (CFRP). It has been designed to be stable with respect to temperature changes, taking also into account dimension variations due to moisture outgassing of the CFRP elements. All the mechanical parts are strictly tolerated to match the alignment and stability requirements imposed for instance by the movable structure which must slide without any jamming. The choice of carbon fiber for the whole main structure system has been made for stability requirements and to minimize mass. Therefore the thermal inertia and the impact over the test specimen will be minimal. The total system weights approximately 13 kg. This makes the system easy to handle by an operator during the installation. For more details see [4].

2.4 Electronics System

The videogrammetry system is controlled by electronic subsystems located inside and outside the thermal/vacuum chamber. The main drivers in the definition of the electrical subsystem are the modularity and fault tolerance. The first is needed to make the system flexible enough to be used with different configurations according to the test. The second is aiming at the reduction (ideally to zero) of the non-recoverable failures that the system might be facing during a test. For more details about electronics system see [4]. The components of the videogrammetric system which are placed inside the vacuum chamber are the harness, mechanical structures, motors, cameras and flashes. The control box, the power supply and the thermal controller are placed outside the vacuum chamber.

3 PHOTOGRAMMETRIC CONSIDERATIONS

The measurement accuracy with photogrammetry is influenced by many factors like: the geometry and quality of the targets, the accuracy of the sensor for image acquisition, the geometrical strength of the network of camera stations, and the processing algorithms. Therefore in order to understand the final accuracy of the measurement, each factor is investigated and analyzed. For our investigation and analysis we consider the requirements of the Herschel spacecraft measurements.

3.1 Quality Control of the Targets

Due to a photogrammetric requirement, which is the availability of sufficient number of pixels for the imaged targets, targets with a size of 30 mm are considered. Two types of targets, flat adhesive retro-reflective and spherical targets, will be used for the Herschel videogrammetry. The quality of the targets in terms of accuracy has been analyzed with two algorithms for image processing: 1) center of gravity of the targets and 2) best-fit ellipse of the target edges.

The difference of target center determination with these two methods is 0.14 micron (0.01 pixel) for flat adhesive targets and is 2.1 microns (15 times larger with respect to the flat adhesive targets) for spherical targets. We investigated the reasons that may cause such a large difference between the results of the two methods of target center determination for spherical targets. In the first step we measured the sphericity of the spherical targets with a Coordinate Measurement Machine (CMM), which has an accuracy of 5 microns + 5 ppm. The sphericity was estimated with statistical analysis of the distance of the surface points from best-fit sphere to the surface points. In all cases the maximum distance of the point from sphere was less than 30 microns. The RMS values of the distances are approximately 5 microns. Considering the image scale, this sphericity may cause 0.21 micron (0.017 pixel) error on the imaged target edge localization thus much smaller value than 2.1 microns is expected as the accuracy of the spherical target center. Therefore the sphericity is not the source of the problem.

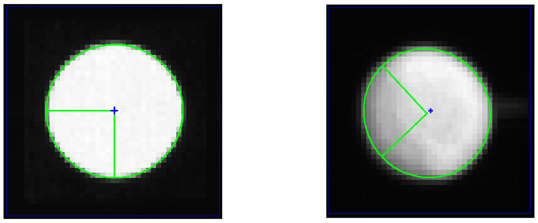

(a) (b)

Fig. 4. Degradation of the target center estimation due to inhomogeneity of target reflectance. a) Flat adhesive retro-reflective target and b) spherical retro-reflective target. The estimated target center from center of gravity method is shown with cross and from the best-fit ellipse target edge is at the intersection of the two lines. The lines are the semi-axes of the fitted ellipses.

Another source of error is the inhomogeneity of the target surface reflectance. Due to the inhomogeneous coating, which shows itself particularly with coating of large spherical targets, the reflectance of the surface is not uniform. Fig. 4 shows the reflectivity of flat and spherical targets. The reflectivity of a flat target is uniform therefore the target center with the center of gravity method and best-fit ellipse method are identical with a difference less than 0.005 pixel. The reflectivity of the spherical target is not uniform and as can be seen from Fig. 4 the target center from two different methods has a large shift (0.7 pixel). This shift appears because the center of gravity method is highly dependent on the gray values of the target while best-fit ellipse target edge depends only on the edge information. As a conclusion, both methods have an error but the error from best-fit ellipse method is smaller.

3.2 Camera Self-Calibration and Point Positioning

A 3D testfield was established at the ESTEC Test Centre, primarily for the camera calibration. However, it will be used for the calibration and accuracy testing of other metrology instruments like theodolites and laser trackers. The testfield consists of 70 flat adhesive targets, which are homogenously distributed in the area of approximately 4.5 × 2.7 meters. This testfield has been used for the micro-camera calibration.

The camera calibration was performed by self-calibration using Browns's set of additional parameters [1] and with two more additional parameters specifically for correcting the affinity and shear of the CCD pixels as shown in Eq. (1). Eq. (1) shows the correction terms to the image point observations.

$$
\begin{aligned}
&\Delta x = dx_0 - \frac{\bar{x}}{c}dc - S_x\,\bar{x} + a\,\bar{y} + \\
&\bar{x}(r^2k_1 + r^4k_2 + r^6k_3) + (r^2 + 2\bar{x}^2)p_1 + 2\bar{x}\,\bar{y}\,p_2 \\
&\Delta y = dy_0 - \frac{\bar{y}}{c}dc - a\,\bar{x} + \\
&\bar{y}(r^2k_1 + r^4k_2 + r^6k_3) + (r^2 + 2\bar{y}^2)p_2 + 2\bar{x}\,\bar{y}\,p_1
\end{aligned}
\qquad (1)
$$

where $r = \sqrt{\bar{x}^2 + \bar{y}^2}$, $\bar{x} = x - x_0$, $\bar{y} = y - y_0$ and with

S_x………	affinity parameter
a………	shear parameter
k_1,k_2,k_3….	parameters of radial symmetrical lens distortion
p_1,p_2……	parameters of decentering lens distortion
dc……….	correction to the camera constant
dx_0,dy_0…	correction to the shift of principal point

The photogrammetric network for self-calibration and point positioning consists of 15 stations with 2 images per station with orthogonal rotation around optical axis (kappa rotation). Since at this stage we are not interested in the absolute value of the coordinates, the scale was approximately determined by distance of two targets of the testfield.

The RMS of the image point residuals was in average 0.020 pixel (0.28 micron) for all micro-cameras. The mean standard deviation of the target center coordinates (one-sigma) is 18, 16 and 26 microns along X, Y and Z coordinate axes (X and Y are lateral and Z is depth axis). These values correspond to a global accuracy of 5 ppm. The mentioned global accuracy is calculated based on the estimated standard deviations from least squares optimization method. It is an internal indicator; it is only valid and realistic if there is no (or significantly small) systematic errors present in the measurement.

In the next section we investigate if the standard deviations estimated from bundle adjustment are realistic values or not. Our investigation is based on independent measurements.

3.3 Accuracy Test with Independent Measurement

A flat granite plate with the dimension of 400×300 mm was considered for an accuracy test. 117 targets were stuck on the plate and the target centers were measured with a Coordinate Measurement Machine (CMM) with an accuracy of 7 microns. After best-fit plane the RMSE of the flatness is estimated to be 4 microns.

The flatness of the granite plate was also measured with photogrammetry. After a best-fit plane to the estimated target coordinates from photogrammetry, the RMSE of the flatness was 7.3 microns. This value is approximately 2 times greater than the RMSE of the flatness (4 microns) from CMM. This deviation can be partially explained due to the fact that optical thickness (which is measured with photogrammetry) does not have the same thickness uniformity compared to the mechanical thickness (which is measured with CMM).

The measure of accuracy with flatness is related to the depth axis of the photogrammetric network. The relative accuracy along depth axis is estimated to be 14 ppm. It should be noted that the coordinate determination along lateral axes with photogrammetry is more precise than the depth axis therefore the global accuracy of the system turns out to be 11 ppm.

3.4 Network Configuration

In addition to the sensor accuracy, the configuration of the camera station and object points (network configuration) influence the accuracy of the object point determination. We investigated the accuracy of the object point determination by computer simulations. The following factors were considered with the simulation:

- the accuracy of the micro-cameras from the result of accuracy tests,
- the reflectivity/incidence angle,
- the influence of the target center shift systematic error because of perspective projection,
- fixed additional parameters to the a priori estimated values.

In a network of 96 camera stations with one scale-bar with a length of approximately 1.5 meter and uncertainty of 20 microns (see Fig. 5 for the network configuration), we obtain a mean standard deviation (one-sigma) of 40, 20, 25 microns along X, Y and Z axes. Due to the special design of the videogrammetric system which enables measurement of large and fixed space structures especially in vacuum and under cryo-temperatures, the established network of the camera stations is not able to on-the-job self-calibrate the cameras. In general, there are few solutions to overcome this problem:

1) Point positioning by fixing the additional parameters to previously determined additional parameters under cryo-temperatures. This requires separate self-calibrations under cryo-temperatures.
2) Point positioning by fixing the additional parameters to previously determined additional parameters under ambient temperature. This requires the use of internal heater for operating the micro-camera at ambient temperature, when they are placed in cryo-temperature environment
3) On-the-job partial self-calibration. This requires the investigation and analysis of the negative influence of additional parameters on the object point coordinates.
4) Hardware modification for a full self-calibration.

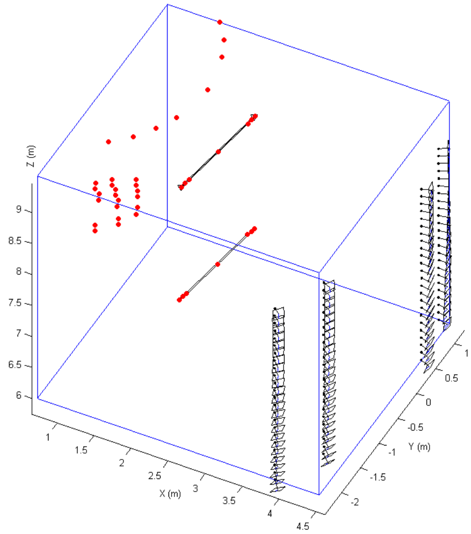


Fig. 5. A Simulated network of 96 stations representing the videogrammetric network of Herschel spacecraft. Two horizontal scale-bars are used.

The first solution requires ad-hoc calibration before the test. The second solution is acceptable if only thermal/vacuum environmental testing is not influenced by the camera thermal perturbation (hot-spots under cryo-temperatures). The third solution is a partial self-calibration of the system under cryo-temperatures, for which a proper strategy is to be considered. The fourth solution is based on the modification of the hardware of the videogrammetric system for a full self-calibration. This approach will be considered in the future. The next section describes this case, which is the preferred one for the Herschel videogrammetric measurement.

3.5 On-the-Job Partial Self-Calibration

As mentioned in the previous section a full self-calibration is not possible with the videogrammetric system due to its specific design. However, a partial on-the-job self-calibration is a solution for the measurement of the Herschel spacecraft.

The negative influence of the additional parameters [6] onto the object point coordinates has been analyzed. The summary of the calculation is shown in Table 1. It shows how the standard deviations of the object point coordinates and the differences from the true values are degraded because of the negative influence of additional parameters. It shows that S_x (affinity parameter) has the highest negative influence on the object point coordinates. Fixing S_x improves the accuracy by a factor 1.4. The other parameter with highest correlation to the object point coordinates is a (shear parameter). After fixing this parameter the accuracy of the object points is improved by a factor 2 with respect to a full self-calibration. Better accuracies can be achieved by fixing more additional parameters. We only consider the case with fixed (S_x, a) because these two parameters will remain constant at cryo-temperatures [7] and it is feasible to fix them to the a priori values, which is calculated at ambient temperature.

Table 1. The negative influence of Additional Parameters (APs) on the object point coordinates. Standard deviations are one-sigma. The units of the standard deviation and RMSE are microns.

fixed APs	highest correlation	std. dev. of	RMSE of	Accuracy improvement
		(X, Y, Z)		
-----	S_x	66, 49, 95	55, 65, 208	↓
S_x	dc, a, dx_0, dy_0	64, 44, 60	130, 49, 72	
(S_x, a)	dc, dx_0, dy_0	61, 40, 52	85, 50, 70	

An additional investigation shows that by fixing (S_x, a) the negative influence of the other additional parameters would remain constant if only the network of measurements (including the point coordinates) had a differential changes (<15 cm). Considering this fact, these errors can be eliminated by subtraction and the point coordinate accuracy can be improved by a factor 2. The mentioned numbers in Table 1 are from computer simulations and may differ from reality. Therefore real tests have been performed in order to validate the result of partial self-calibration and accuracy improvements. The results are presented in next sections.

3.6 Qualification of the System

Each component of the videogrammetric system has been separately validated for operation in ambient and cryogenic conditions. The overall operation of the system in cryo-temperatures has been qualified during the pre-test of the Large Space Simulator (LSS) for GOCE spacecraft.

The validation of the videogrammetric system accuracy has been done for each micro-camera separately after an investigation of their potential accuracy. The accuracy of the overall videogrammetric system was estimated through computer simulation. However, it was obviously necessary to confirm this estimate in a real situations. A setup as shown in Fig. 6 was prepared and it represents approximately the Herschel spacecraft target configuration with 12 spherical and 20 flat adhesive targets. Two independent measurement methods have been used:

- A laser tracker: for the measurement of the spherical targets only, since the center of flat adhesive targets cannot be measured directly with laser tracker,
- A theodolite: for the measurement of the center of the flat adhesive and some of the spherical targets centers.


(a) (b)

Fig. 6. A dummy object (a) and the videogrammetric system (b) in the Hydra clean room at ESTEC Test Centre. It shows the location of the spherical (top at the rim) and flat adhesive targets (on the body and lower than the spherical targets) simulating the configuration of the Herschel spacecraft (copyright ESA-ESTEC).

In total five different cases for accuracy tests have been compared:

1) videogrammetry and laser tracker measurements,
2) videogrammetry and theodolite measurements for spherical targets,
3) videogrammetry and theodolite measurements for flat adhesive targets,
4) partial self-calibration,
5) improved partial self-calibration.

The accuracy of the probed points on the surface of the spherical targets was estimated with a laser tracker simulation software, Spatial Analyzer, which is 38, 45 and 43 microns along X, Y and Z axes. By error propagation through best-fit sphere the accuracy of the spherical target center measurement was estimated 18, 20 and 22 microns along X, Y and Z axes. The RMS of the difference of the spherical target center coordinates from videogrammetry and laser tracker is 100, 110 and 73 microns along the X, Y and Z coordinate axes. This relatively large RMS value is due to the poor quality of the spherical targets that cannot be measured accurately with photogrammetry.

The accuracy of the flat and spherical target center measurements with theodolite is 70, 60 and 90 microns along X, Y and Z axes. The RMS of the difference of the target center coordinates from photogrammetry and theodolite measurement is 80, 100 and 100 microns along the X, Y and Z coordinate axes. If we only consider flat adhesive targets the RMS of the coordinate difference becomes 70, 40, 70 microns. The RMS of the point coordinate differences from a case with a partial self-calibration and a case with fixed additional parameters is equal to 108, 46 and 82 microns, which are approximately equal to the results of simulated network. A part of this difference can be explained by the difference between the simulated network configuration and the real network configuration for validation. After fixing (S_x, a) the pattern of the negative influence of additional parameters does not change significantly by a small change of the network configuration. Therefore it is able to improve the accuracy by a subtraction of the point coordinates of two sets of measurements down to 51, 55 and 46 microns. Therefore the accuracy obtained from videogrammetry fulfills the requirements of the Herschel spacecraft measurements (50 microns one-sigma).

4 SUMMARY AND CONCLUSIONS

A videogrammeric system was developed by ESA-ESTEC Test Centre for the measurement of spacecrafts. The system has the following specifications:

1) low thermal perturbation of the specimen in thermal/vacuum testing due to the operation of the whole system at cryo-temperature. The cameras are able to operate at temperatures down to -120 ºC without using any canister
2) no systematic errors introduced by light refraction at the interfaces of a viewing port with non-space qualified sensor (multi-media photogrammetry)
3) due to its design operation, it does not require the movement/rotation of the specimen, especially useful/important when the spacecrafts is restricted to be fixed during thermal/vacuum environmental testing
4) it is portable, flexible and convenient for the thermal/vacuum monitoring tests of the large space structures and it is compatible with different space simulator facilities

Quality control tests in order to qualify the videogrammetric system in terms of operation at cryo-temperatures were performed successfully. In terms of accuracy, parameters like the quality of targets, the accuracy of the micro-cameras, and the potential accuracy of the whole videogrammetric system were investigated. Special measures were taken into account for the first videogrammetric application, which is the measurement of the Herschel spacecraft. The results indicate the readiness of the system for thermal/vacuum environmental testing and the reaching of accuracy goals.

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