Close Range Photogrammetry:
A Tool for Shape Measurement & Reflector Alignment

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Abstract

The integration of large and deployable reflectors onto communication satellites is one of the more difficult tasks undertaken at ISRO. Apart from CFRP/dual grid antennae, which vary from 2meters to 3meters in size, larger unfurlable antennae of about 6meters diameter are considered in the spacecraft configurations at ISAC, ISRO. This requires a 3D measurement system that can be used at elevated heights for range testing (CATF) and thermo-vacuum environment areas to quantify gravity and temperature induced distortions. At the same time the system should be non-contact, reliable and highly accurate. Existing techniques such as ECDS, Laser Tracker & CMM fall short of some of these considerations.

A study has been undertaken by Mechanical Integration Division, ISAC, for evaluating Close Range Photogrammetry (CRP). The study involved a number of case studies on carefully selected test objects to study the advantages of CRP over the existing measurement techniques currently being employed. After verifying the accuracy potential of CRP, it was successfully implemented for shape measurements and alignment activities of Ka-Band reflector of the Spacecraft, which is to be launched into geostationary orbit. This paper provides an overview of the various 3D measurement systems employed at ISRO and describes the comparison made among Laser Tracker, ECDS, CMM and CRP via a number of case studies. The paper further deals with the measurements of Ka-Band reflector of the Spacecraft, which is to be launched into geostationary orbit.

Keywords: Close Range Photogrammetry, Antenna Alignment, Communication Satellite

Abbreviations:

CRP	Close Range Photogrammetry
CATF	Compact Antenna Test Facility
ECDS	Electronic Coordinate Determination System
CMM	Coordinate Measurement System
ISRO	Indian Space Research Organisation
ISAC	ISRO Satellite Centre
MID	Mechanical Integration Division
AIT	Assembly Integration and Testing

I. Introduction:

ISRO Satellite Centre is India's National Satellite Assembly Integration and Test facility. The facilities at ISAC are used for integrating & testing of wide variety of Satellite systems for remote sensing and communication applications and cover a wide frequency range.

The spacecraft alignment section, MID at ISAC is responsible for the measurement of deviation, and correction of orientation and position of various spacecraft elements with respect to the spacecraft axes. MID is well equipped with the latest 3D measurement systems available and is constantly looking at new ways to improve existing spacecraft measurement and alignment processes.

3D measurement is an ever expanding field with constant improvements to accuracy, efficiency and usability. In the past few decades a number of 3D measuring systems have evolved. [1-7]. Close Range Photogrammetry is one of the most promising techniques that are emerging for non contact type measurement applications. To the best knowledge of the authors, a very few steps have been taken to develop the applications and procedures to make the measuring system more effective and versatile in the field of alignment of spacecraft elements including reflectors.

It was conceived that CRP has several inherent advantages for spacecraft alignment applications, particularly in terms of speed, accuracy, repeatability, ease of operation and minimizing manpower to complete tasks. Various studies were undertaken and several 3D measurement systems, including CRP were evaluated by MID. Upon completion, the CRP system manufactured by Geodetic System Inc. (GSI) was selected. The system selected was the VSTARS/S8 with the INCA3a+ camera researched, designed and manufactured by GSI. Based on the studies carried out, the V-STARS Photogrammetry system from GSI was found to be superior in all the key evaluation categories.

The specifications and reference data was generated using different measuring systems (viz. CMM, Laser Tracker, ECDS, Optical devices, RF Signals etc.) at the subsystem level. Transformation of the references provided at the subsystem level (in the form of tooling balls and reflective mirrors) to the CRP compatible retro-reflective targets is an evolved process which is carried out as developmental work. At present the ECDS is the most commonly used tool for measuring antenna and feed orientation with respect to the spacecraft. It has been observed that this system provides an accuracy of 0.050mm to 0.100mm and consumes comparatively greater number of man-hours. The use of the ECDS system to measure the relative orientation of feed and antenna becomes near impossible at CATF, wherein the spacecraft is mounted at an elevated height of about five meters above the ground.

A procedure to precisely measure the relative orientation of feed and reflector with respect to the Spacecraft axis with the use of the V-STARS Photogrammetry system has been developed by the authors. Results achieved are far better than that of the existing ECDS system. Additionally, the reflector alignment time per satellite can be brought down to $1/10^{th}$ of the time taken by the conventional ECDS method.

Reduction of measurement time and manpower needed to complete this measurement and also improving on overall accuracy is an overwhelming advantage. This is even more significant in view of the growing number of integration tasks, with tighter time schedules on a growing number satellites projects undertaken.

Various case studies were undertaken to compare CRP, ECDS and Laser Tracker methods. The case studies selected encompass antenna measurements right from the mould level to fully integrated antennae at spacecraft level and finally at CATF during various scan angles for RF characterisation.

II. 3-D Measuring Systems at a glance:

A. Coordinate Measuring Machine:

A CMM (Fig. 1) is a contact type of measurement system, wherein probing is required to be done at the point of interest. Jointed arm-CMMs use an anchored articulated arm attached probe tip at the movable end. The length of each arm section is combined with the encoder angle at each joint to compute the probe's position. The machine recognizes the probed point and gives the 3-D coordinates of the same.

Figure 1: Coordinate Measurement Machine

B. Theodolite Based Optical Measuring System (Autocollimation):

Autocollimation (fig.2-3) is the process of sighting with a telescope focused to infinity to an optically flat mirror. In order to carry out autocollimation, the telescope reticule must be illuminated from the eyepiece side. A silhouette of the illuminated cross hairs is projected onto the mirror and reflected back to form an image in the plane of cross hairs. If the mirror is exactly at 90^0 to the line of sight the cross hair coincide with their reflected image. The tilt of mirror is read using the encoders of the theodolite which gives reading in horizontal and vertical reference planes.

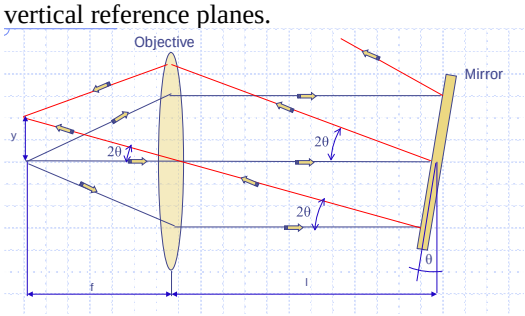

Figure 2: Autocollimation Principle

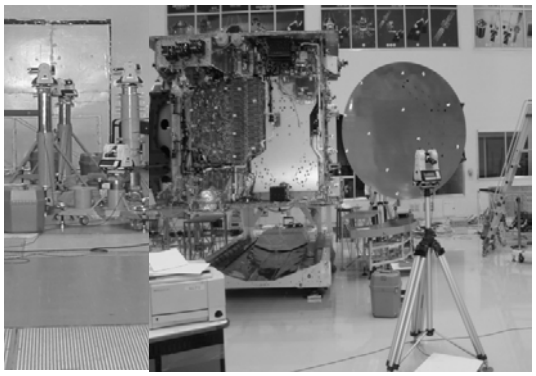
Figure 3: Equipment used for Autocollimation & ECDS

C. Electronic Coordinate Determination System (ECDS):

In this technique, point coordinates are measured via intersection from theodolites rays (minimum 2)**.** Typically, points are identified using physical targets such as tooling balls, cross hairs as features on the object. The operators aim two telescopes at a target in space. Digital encoders register the relative angular positions of the two theodolite heads with respect to a reference coordinate system. A computer uses the principle of triangulation to determine the coordinates of target positions.

D. Laser Tracker:

Operationally, a laser tracker measures two angles and a distance. The tracker sends a laser beam to a retro-reflective target held against the object to be measured. Light reflected off the target retraces its path, re-entering the tracker at the same position. Retro-reflective targets vary, but the most popular is the Spherically Mounted Retro-reflector (SMR). As light re-enters the tracker, a part of it goes to an interferometer that measures the distance from the tracker to the SMR.

Figure-4 shows a person locating a retro reflector target on the feed and antenna. The helium-neon laser travels to the retro target and back into the interferometer. Angular encoders of the laser tracker measure the angular

orientation of the tracker's two mechanical axes: the azimuth axis and the elevation axis. Measuring the encoder's angle and the interferometer's distance is sufficient to locate precisely the SMR's (target) center.

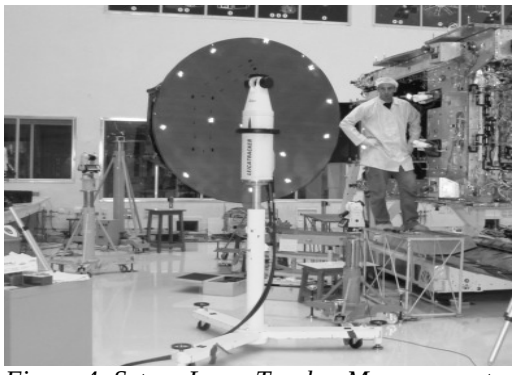

Figure 4: Setup- Laser Tracker Measurement

E. Close Range Photogrammetry:

Photogrammetry uses the basic principle of triangulation whereby intersecting lines in space are used to compute the location of a point in three dimensions. These lines are generated by photographing all the target points from different positions using a 'metric' camera such as the INCA3a+ shown in Figure 5. However, in order to triangulate a set of points one must also know the camera position and aiming angles for all the pictures in the set. A process called "resection" which is carried out by the V-STARS software automatically resolves it without human intervention and via the use of a process known as Bundle Adjustment, the coordinates of each point is computed by the software.

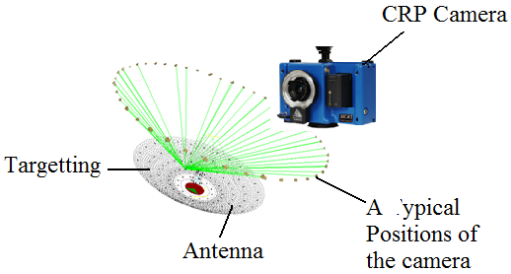

Figure 5: Close Range Photogrammetry

III. Case Study 1: Reflector & Feed Alignment of a spacecraft to be launched into geostationary orbit.

A. Objective:

Three independent measurement systems viz. ECDS, CRP and Laser Tracker were used for alignment measurement for deployable antennae systems at spacecraft level. The results obtained were compared and the advantages/limitations of each method of measurement are reported.

The shape measurement and RF characterization of the reflector and feed is carried out at subsystem level, wherein the relative position and orientation of the feed with respect to the reflector is finalized and the reference is transferred to the tooling balls present on the reflector and feed system. Once the reflector and feed are assembled on the spacecraft, the coordinates of tooling balls are measured in spacecraft coordinate system, which in turn provides three rotation angles and translation distances of the reflector & feed in spacecraft coordinate system. Deviations observed from specifications generated at subsystem level may need correction, and thereafter measurements are carried out to find out the final position and orientation. A study was taken up during this measurement to compare the three systems with the following objectives:

1. To compare the values obtained using all the three techniques of alignment viz. ECDS, CRP and Laser tracker

2. To implement the CRP technique for feed and reflector alignment at spacecraft level.

3. To compare the man-hours required by each system to measure the feed and reflector orientation.

4. To evaluate the ease of using each equipment.

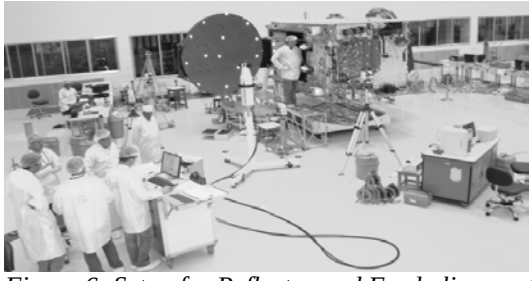

Figure 6: Setup for Reflector and Feed alignment using ECDS, CRP and Laser tracker

B. Measurement Steps:

1. A common spacecraft coordinate system is defined and established using all the three methods on a leveled surface table.

2. The coordinates of the tooling balls on the spacecraft, feed and reflector are measured using all the three methods with respect to the common coordinate system.(Fig.6)

3. To make the tooling balls compatible for measurement by all the three systems, a specialized adapter is designed which accommodates interchangeable targets within the accuracy of 0.002mm.

4. The coordinates of the tooling balls on spacecraft, feed & reflector were compared.

5. The relative angles between spacecraft, reflector and feed axis are derived using the measured tooling ball coordinates and compared for all the three systems.

C. Observations Made:

A comparison between the differences of measured coordinates using CRP & Laser Tracker (LT) is shown in the following graph (Fig.-7). The graph shows that all the differences lie within 0.040mm.

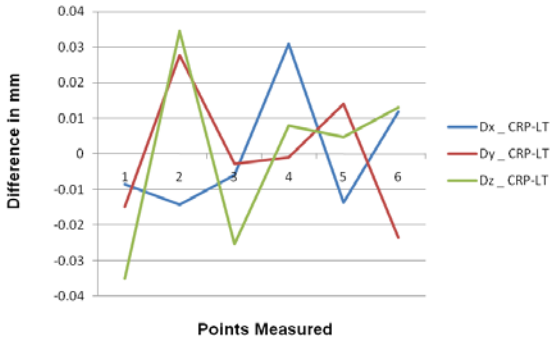

Figure 7:-Comparison between CRP & Laser Tracker

The difference between the measured coordinates of CRP & ECDS lie within 0.150mm. (Fig.-8).

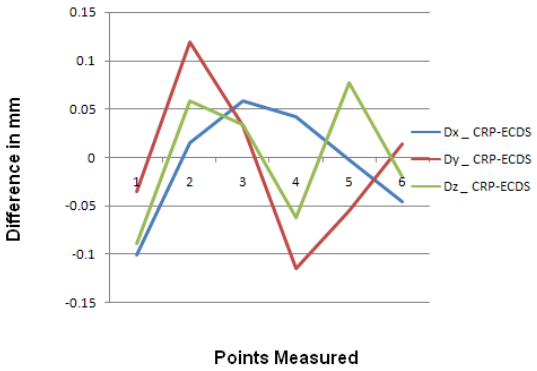

Figure 8:- Difference Between CRP& ECDS

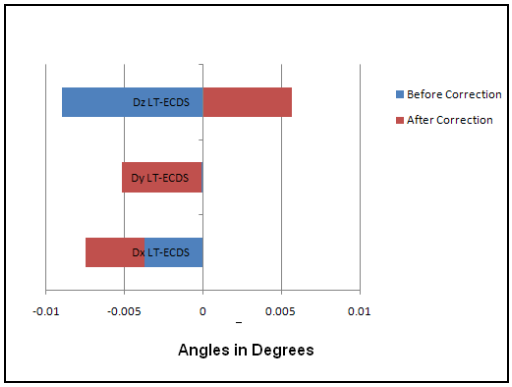

Figure 9: Difference in Angles (Deg) Derived By LT & ECDS

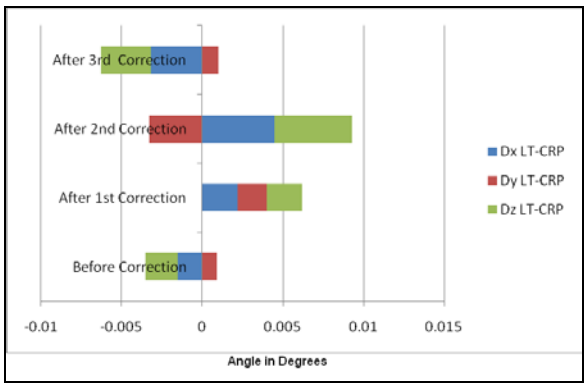

Figure 10: Difference in Angles(Deg) Derived By LT & CRP

The relative angles of feed and reflector axes with respect to the common coordinate system is derived from the tooling ball coordinates and compared with the design specifications. Four iterations were carried out to correct the deviations observed. The graphs (Fig 9 and 10) show the comparison between Photogrammetry, Laser Tracker & ECDS. The difference between the angles measured shows a close match within 0.015deg.

The field time required for the acquisition of the specimen data was compared between the techniques. The ECDS measurement of the specimen took 7 hours, compared to 2 hours for laser tracker and 15 minutes for the photogrammetric (CRP) measurement. For the post-processing of the acquired data, half an hour was spent on the ECDS and laser tracker data and 15 minutes on photogrammetry. The manpower requirement in case of CRP is one person as compared to two for laser tracker and three for ECDS. Unlike ECDS and Laser Tracker, CRP does not require any steady or isolated spacecraft setup for measurement. The above mentioned observations are summarized in table1.

Table1: Time and Manpower comparison between various metrology methods

	ECDS	**LT**	**CRP**
Preparation time	3hrs	1hr	30 min
Time to acquire	7hr	2hr	15min
Post processing	30min	30min	15min
Manpower (person)	3	2	1

IV. Case Study 2: Contour & Shape Measurement of a Ka-Band Antenna Mould for geostationary spacecraft:-

A. Objective: The Ka Band antenna of the spacecraft consists of four antenna segments integrated in one mould. An attempt is made to measure the shape and contour of the four segments of Ka-Band antenna using the V-STARS Photogrammetry system using regular Photogrammetry targets as well as a specialized targeting accessory known as PRO-SPOT. Since the V-STARS system offers the advantage of executing a measurement at any required orientation of the antenna, this attempt was made to compare the accuracy between CRP and CMM and also to study different possible advantages of using CRP for antenna shape measurement.

B. Measurement Steps:

1. At the time of starting CRP measurement, the antenna mould was placed on the CMM machine for measurements of contour coordinates, and around 2500 numbers of CRP targets were stuck on the mould at appropriate regular intervals on all the four segments of the mould. (Fig.11-12)

2. A CRP compatible hemispherical target ball of 1” diameter is placed on the reference hole to derive the hole centers, which were used as a common reference for CMM and CRP measurements.

3. Points were captured using CRP and coordinates of targeted points were obtained.

4. Coordinates of the measured points (by CMM and CRP) were compared.

5. For post processing, the shape from the data of measured points on the reflector was derived & compared.

C. Observations:

1. The measurement time taken by CRP was about two hours, which includes targeting and data capture time as compared to 20 hours for CMM measurement including setup.

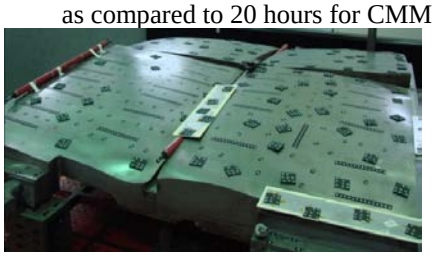

Figure 11: CRP Setup for Shape Measurements of Ka-Band Antenna Mould

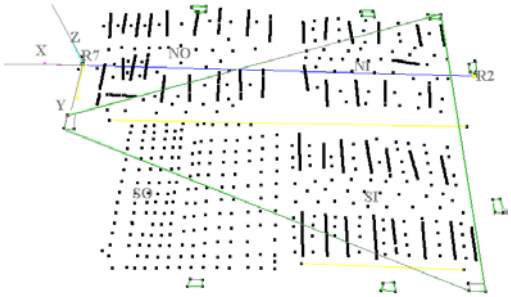

Figure 12: Points cloud generated by CRP.

2. The comparison shows that CRP measured values lie within the accuracy range of the CMM.

3. One quadrant of the mould is paraboloid. The data acquired was used to fit a parabola and the result shows an RMS of 0.031mm for CRP as compared to 0.035mm for CMM.

4. Unlike CMM, CRP measurement does not require a special setup and the measurement can be repeated at any orientation of the specimen and at any stage of spacecraft integration.

V. Case Study 3: Target-less Shape Measurement of Ka-Band Antenna of a geostationary Spacecraft Using GSI’s proprietary Pro-Spot Target Projection System.

A. Objective:

After successful demonstration of accuracy parameters on the mould of a Ka-Band antenna, it was planned to evaluate GSI’s PRO-SPOT target projection system which enables target-less shape measurement of the antenna. In this case study it is demonstrated that thousands of points can be projected on the surface of the reflector. The 3D coordinates of these projected points can be measured using V-STARS in much the same way that normal targets are measured. This technique offers advantages of measuring shape of the reflector at any orientation and at various phases of AIT of the reflector. The technique is non-contact, faster, and more accurate. Usage of this system can be further extended to measure real-time shape and distortion of the antenna during CATF test which is not possible using any other techniques.

Figure 13a and 13b provide details of the setup used for the measurements carried on Ka-Band reflector using Pro-Spot. Fig.14 shows the shape derived using points measured by Prospot.

Figure 13a: Setup for Shape Measurement Using Pro-Spot Target Projection System

Figure 13b: Setup for Shape Measurement Using Pro-Spot Target Projection System

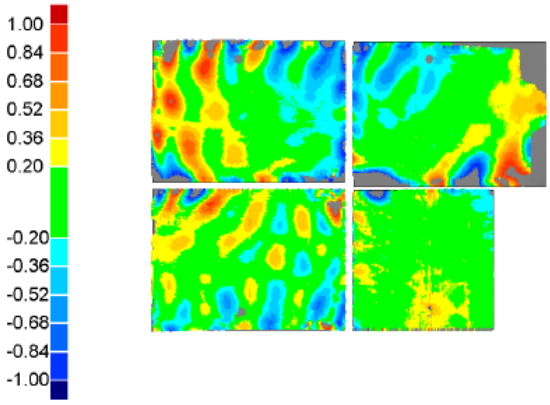

Figure 14: Shape derived using 90000 points measured using Photogrammetry with Pro-Spot

B. Observations: The comparison shows that the CRP measured values lie within the accuracy range of the CMM.

VI. Case Study 4:Measurement of gravity induced distortions of the antenna at CATF:

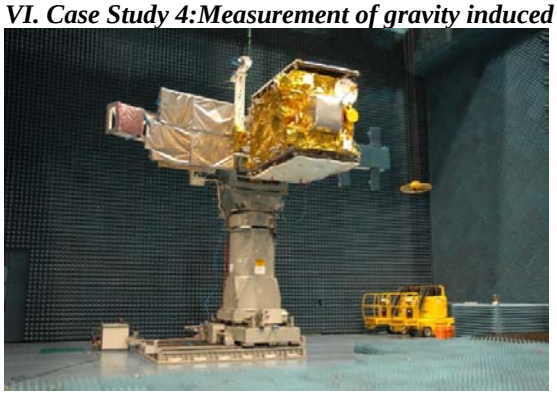

Figure 15: Spacecraft Positioned on DUT at CATF

A. Objective:

CATF is configured to carry out antennae characterization and also for checkout of the fully integrated spacecraft with antenna and other subsystems. The CATF is used for the measurement of radiation pattern, gain, return loss, cross polar isolation, precise identification of the bore sight axis, EIRP and G/T of the transponder under the simulated zero-gravity environment. During the test, the spacecraft is positioned on the Device Under Test (DUT) positioner, which is about 5mts above ground, in order to match the nominal reflector bore sight with the Nominal plane wave axis (NPA) of the Facility.

Special fixtures are used to simulate the zero-gravity environment.(fig.15). The objective of CRP measurement is to quantify the mechanical distortion numbers on reflector at various scan angles of DUT which validates effectiveness of the zero-gravity fixtures.

B. Measurement Steps:

1. The fully integrated spacecraft is positioned on DUT positioner and the reflector is deployed. Special fixtures are used to simulate Zero-gravity environment.

2. The special fixture provides a rigid connection between the spacecraft, reflector and DUT positioner. CRP measurements are carried out to find out the relative distortions of reflector with respect to the spacecraft during various scan angles of the DUT, positioned in steps of 1degree.

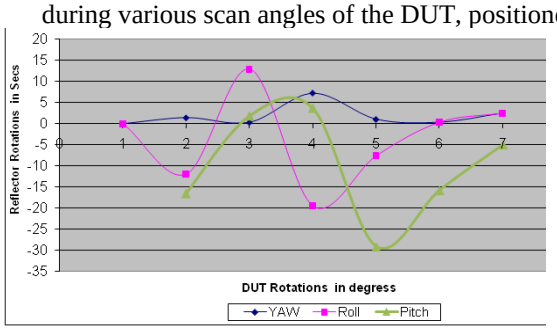

Figure 16: G-Effect on Reflector Due to DUT Rotation

C. Observations:

1. It becomes a very tedious and time consuming job using Laser Tracker and ECDS to perform measurements at a height of 5mts from the ground and this is why this kind of measurement has not been attempted earlier. CRP has made this job very simple and all the seven sets of measurement are completed within about 2 hours.

2. The measured data (fig.16) shows the relative distortion of the reflector is well within 30 arc sec (0.008deg), which shows the rigidity between the spacecraft and reflector exists during various scan angles of the DUT position and hence the purpose of special fixture for gravity compensation is met.

VII. Conclusion:

After a number of case studies and measurements, the V-STARS CRP system was successfully applied for alignment of reflector systems for spacecraft with considerable advantages in terms of, greater accuracy, flexibility, reliability and reduced man-hours.

The comparison between ECDS, Laser Tracker & CRP show that the values of CRP lie between 0.005mm to 0.020mm as compared to that of ECDS (0.050mm to 0.100mm) and Laser Tracker (0.020 to 0.050mm.)

The system is also used to study shape parameters of the reflector and gravity induced distortions on the reflector at CATF, which is very difficult to carry out with any other technique of measurement.

Concluding the test conducted show that the V-STARS CRP system can easily replace ECDS and Laser Tracker systems for alignment activities on reflector, feeds and other sub systems on spacecraft.

The V-STARS CRP system has been successfully implemented at ISRO for alignment activities of Antenna and Feed Systems for a spacecraft to be placed in geostationary orbit. To support the argument, the satisfactory results of RF characterization show that the alignment results achieved with Photogrammetry are within the tolerance limits.

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