Technology Transfer for a 360 Scanning LiDAR

Adam Deslauriers*, Sean Zhu*, Mike Sekerka**, Evan Trickey**

*Neptec Design Group
e-mail: adeslauriers@neptec.com

**Neptec Technologies Corp
e-mail: msekerka@neptec.com

Abstract

Neptec Design Group, in partnership with the Canadian Space Agency (CSA), has made substantial investments in developing an advanced 360° scanning LiDAR technology for vehicle-based mapping, hazard avoidance, and situational awareness. This program, the Integrated Vision, Imaging and Geological Mapping Sensor (IVIGMS) began with a contract from CSA which consisted of an extremely challenging design and build program that culminated in a very successful demonstration (at TRL 4) of 360° scanner technology at CSA's Mars yard. Neptec has now "spun-out" the technology to commercial terrestrial markets through a commercialization program executed by Neptec Technologies Corp. This paper provides an overview of the novel scanning architecture, it's applications for space and Earth, and aspects of the technology transfer effort.

1 Introduction

To date, autonomy concepts for rover missions have made use of stereo vision as the primary source of 3D data for localization, mapping and hazard avoidance. In order to push the boundaries of rover autonomy, increased sensor performance and reliability is necessary, but unfortunately the performance limitations of stereo cameras have been reached. On Earth, stereo cameras have long ago given way to a variety of scanning LiDAR products in autonomous vehicles such as those in the DARPA Challenges and the Google Driverless Car. LiDARs present an enticing opportunity to generate long-range, accurate, lighting-insensitive 3D measurements. As in terrestrial applications, stereo cameras will be replaced with LiDAR on space programs as well, and CSA has recognized and supported this development of the next generation of scanning LiDARs for Space applications.

The IVIGMS LiDAR sensor was developed for planetary rover applications with a focus on situational awareness, mapping and hazard avoidance. Using a novel, patent-pending spinning prism design, it is able to scan rapidly over a field of view of 360° in azimuth and 45° in elevation. The sensor is random-access, meaning the operator can command any desired beam trajectory. Several pre-programmed trajectories are provided that are tuned to rover-based mission objectives. High-rotation rate scans are employed for situational awareness and hazard avoidance. High resolution (lower rate) scans are also possible for detailed mapping requirements. Hybrid scans provide the best of both worlds employing phase-shifted high rate scans that repeat at slightly different angles each pass to fill the gaps left in previous passes.

2 Overview of the 360 Scanner Program

The program to develop a 360º scanning LiDAR originated with a CSA Request for Proposals which described a basic need for a compact, high-speed LiDAR for situational awareness, mapping and hazard avoidance for rover-mounted applications. The sensor was required to cover a Field of View (FOV) of 360º x 45º cover that area in a matter of seconds. An intense period of development followed with Neptec pursuing several concept designs that could produce a workable combination of high-speed scanning (for driving) but also high resolution (for mapping). This was accomplished through a phased approach to the development.

2.1 Definition Phase

The project began with a critical review of the many mandatory requirements. A use-case was assembled for the sensor which specified how the users would interact with the system to provide guidance to the design process in the cases where functionalities may not be captured in the requirements. The compliance matrix was prepared that contained these analyses, which formed the input to the development of the Performance Evaluation Criteria (PEC). These parameters, deemed to be the critical requirements were chosen to be FOV, point density, and scan rate.

2.2 Design and Build

The design phase was divided by discipline into Opto-mechanical, Electrical, and Software design. Due to the challenging nature of the IVIGMS performance requirements, it was clear that a novel scanning approach would be required; therefore, the early emphasis in this phase was on the opto-mechanical design. Several concepts were evaluated at the beginning of the project and were evaluated against the PECs above. The conclusion of the design phase was the proposed design depicted in Figure 1.

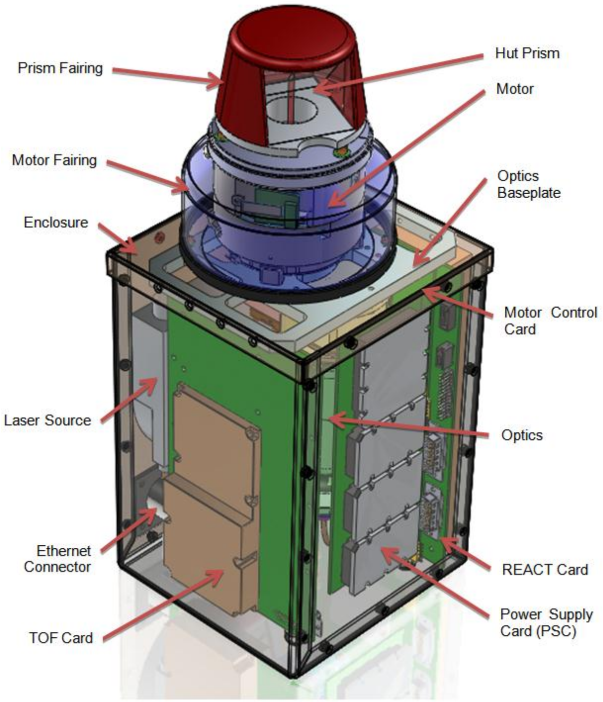

Figure 1 – Integrated Vision Imaging and Geological Mapping Sensor

The design consists of a rectangular arrangement of circuit cards to optimize heat dissipation and eliminate the need for cooling fans. This makes the IVIGMS more appropriate for use in the vacuum of space and makes the system more robust to environmental constraints on the ground.

Four circuit cards (plus a power supply card) were developed or adapted for this program. In the interest of maximizing the flight worthiness of the design, the time of flight receiver card and the processor card are direct descendants from Neptec's successful TriDAR [1] program which flew aboard Space Shuttle flights STS-128, STS 131 and STS 135.

The circuit cards are arranged surrounding a central monostatic transmit / receive optics that project the laser into the scanning motor prisms, and also receive, through the same aperture, the return pulses.

2.3 Novel Scanning Approach

The most innovative of the IVIGMS subsystem are the scanning optics. The optical scanning approach features two hollow shaft motors with prisms in a geometry similar to that of a Risley prism. Neptec's patent-pending modification to this arrangement sends the beam out of the scanning system at 90º compared to a typical Risley prism by way of a "Hut" prism, named for its shape.

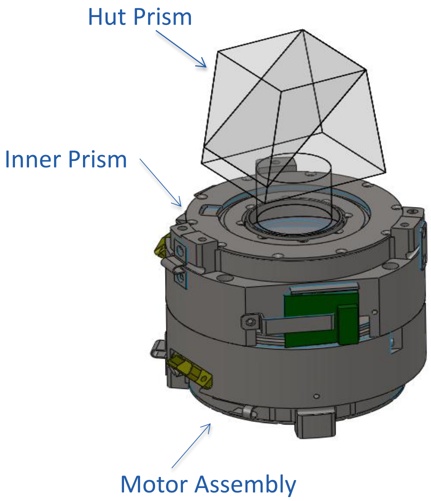

Figure 2 – IVIGM Scan Optics

The motors can be controlled independently and rotate from 0-30Hz (Hut Prism) and 0-100Hz (inner Prism). This results in a novel scan pattern that generates a repeating spiral pattern (Figure 3).

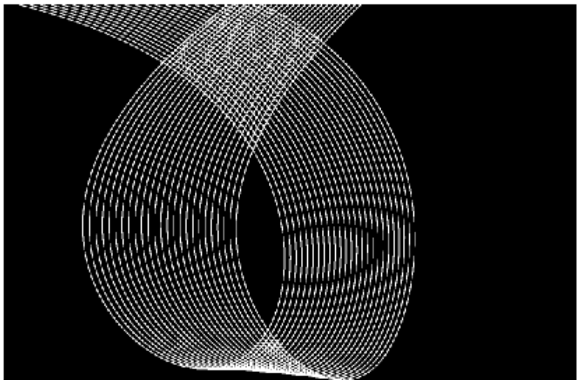

Figure 3 : IVIGM Scan Pattern as it is projected outward

The gaps between the individual loops of data are controlled by the speed of the hut prism as a fraction of the speed of the inner prism. By controlling the ratio between the inner and the hut prism, the loops gathered on each rotation of the hut prism can be projected in the gaps left by the previous rotation. This has the practical effect of increasing the density of the scan data by simply allowing the sensor to scan for longer. Figure 4 shows 2 seconds of data while Figure 5 shows the impact of allowing that scan pattern to repeat for 8 more seconds (for a total of 10 seconds).

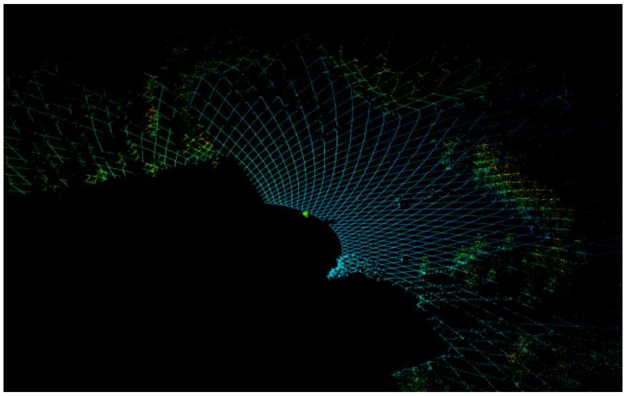

Figure 4: 2 seconds of data of a parking lot

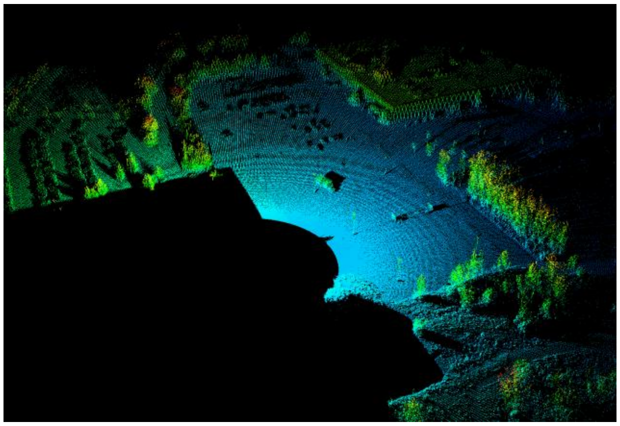

Figure 5: 10 seconds of data from the same scan. Note how subsequent rotations from the hut prism fills in the gaps left by the previous pass.

2.4 IVIGMS Final specification

The resulting Integrated Vision Imaging and Geological Mapping Sensor (IVIGMS) met the challenging requirements while producing a sensor with considerable opportunities for both space and terrestrial applications. The system specifications are listed in Table 1:

Table 1: IVIGMS Specification

Laser	1540 nm pulsed laser
Laser Beam Divergence	0.3mrad
Laser Safety	Eye safe (through hardware interlock, NOHD <75cm)
Sensor Field of View	360^0 x 45^0 (elevation -35^0 to $+10^0$)
User configurable Field-of-View	Yes (dynamically under software control)
Data Acquisition (user configurable)	25kHz to 200kHz
Scan Speed	30 revolutions per second
Range @ 80% reflectivity (min/max)	3m - 200m @ 200kHz, 3m - 1km @ 25kHz
Range Accuracy / Range Precision @ 150m	1cm / 0.5cm
Size	46cm x 17cm x 17cm
Weight	7.3kg
Power consumption	100 Watts (at max scan speed)

2.5 Scan Coverage Analysis

CSA's specification for the IVIGMS called for a sensor with 3mrad point spacing. Taken over a 360º x 45º FOV, this results in a required scan of 2094 x 261 pixels, assuming regular point spacing. The IVIGMS scan data, however is not arranged in a regular grid of points but rather by spirals, making it a "disorganized" point cloud by nature. This complicates the analysis of point spacing since the "nearest neighbor" to a point is not necessarily the one that follows it in the scan data, due to the nature of the scan trajectory that crosses itself with each loop. A comparison of the IVIGMS scan statistics was required to verify that the unique scan pattern generated by the IVIGMS was meeting the intent of the 3mrad requirement. Moreover, it was important to demonstrate the real-world implications of the scan pattern in its intended application, as a rover-based scanner.

To analyze the point spacing, the IVIGMS scan data was gathered and the angles of the scanning beam were extracted. These scan angles were then used to project the scan points onto a virtual cylinder surrounding the sensor, and Delaunay triangulation was used to calculate the distances (vertices) between these points. These distances were then converted back into angular measurements at which point statistics were gathered on the angular point spacing. These Statistics are shown in Table 2 in degrees. A 2nd analysis projected the points on plane located 1.5m below the scanner. This represents the ground coverage of the IVIGMS scans and returns a point cloud of scan data as if it were projected on an infinite flat terrain. The statistics for this analysis are shown in Table 2 in mm. The statistics for the plane projection were limited to points on the plane from a distance of 3m (where the first points strike the plane) to 100m since point spacing becomes exponentially large as distance from the rover increases.

This analysis was repeated for a similarly arranged regular scan of 2094 x 261, referred to as the "Specification" scan in Table 2. Because Delaunay triangulation calculates the distance between all points, the maximum angle between two points in a uniform grid of 3 milli-rad would not be 3 milli-radians, it would be the hypotenuse of the triangle formed between any three of the points, which is 4.2 milli-radians.

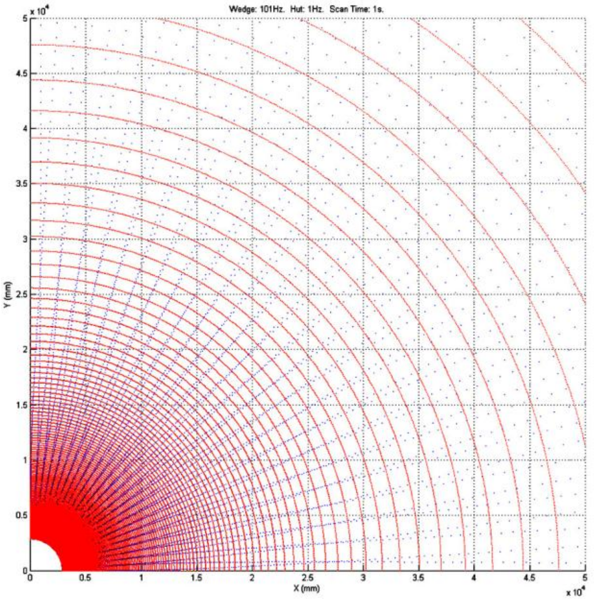

Figure 6: Projected scan density of the Specification Scan (Red Circles) vs a 1s IVIGMS scan (Blue) with axes from 0m-50m.

The imagery and statistical analysis both highlight the fact that the average angular resolution falls with the specified range of ~3mrad when the IVIGMS scan time has reached 5 seconds, however, the mean distance between points on the ground has surpassed the specification requirements after a scan time of only one second. This difference is shown in Figure 6. The apparent disagreement between angular and ground plane statistics manifests itself in the scan ground pattern plots as an increased distance between scan lines on the ground as range increases. The IVIGMS does not suffer as much from this effect as the spinning line scanner, sacrificing spot density at nearer ranges for increased spot density at greater ranges.

2.6 Demonstration at CSA's Mars Yard

A demonstration of the sensor capability in a realistic environment was performed during the last phase of the project to meet the mandatory requirement. The key performances metrics and the prototype capabilities were demonstrated at CSA's Mars yard in October 2012.

For the demonstration, IVIGMS was mounted on a JUNO rover. The JUNO rover was developed by Neptec for CSA on a separate program to develop an adaptable work-horse lunar rover concept [2]. This configuration is shown in Figure 7.

Figure 7: IVIGMS mounted on a JUNO rover

The testing included a variety of fast and slow scans to demonstrate the full range of operational scenarios. One of the longer, high resolution images is included in Figure 8. This scan was acquired over the course of 3 minutes with a maximum range exceeding 1km.

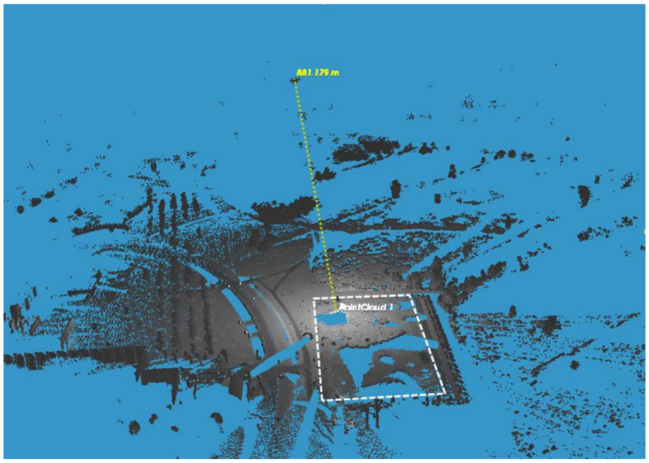

Figure 8: Long range mapping scan of the CSA Mars yard (highlighted rectangular area) and beyond.

3 Technology Transfer for Commercial Use

The technology developed under the IVIGMS program was novel and compelling in its capabilities. It was therefore an excellent candidate for commercialization. Several industrial applications benefit from the rapid, high resolution scanning of a 360º field of view. Neptec secured two patents associated with the scanning concept (with a third patent pending), and is now actively selling 360 LiDAR scanners to terrestrial industries including Mining, Offshore Oil & Gas, and Defense & Aerospace. This section outlines the approach taken for commercialization, and the improvements made along the way.

3.1 OPAL-360

In 2011, Neptec created Neptec Technologies Corp (NTC) as a separate company with a dedicated team focused on commercialization and product development for terrestrial markets. This decision was driven by the differing needs between space programs and commercial production. The IVIGMS design was adapted for NTC's OPAL product line as the OPAL-360. This evolution of the design upgraded many of the sensor capabilities and specifications.

This second generation of scanning product shares much of the internal architecture of the original design, as well as the same general specifications with a few key upgrades. Among the improvements was a more rugged enclosure, an optical dome for improved environmental protection, (Figure 9) and the integration of Neptec's OPAL (Obscurant Penetrating Auto-synchronous LiDAR) dust penetration technology.

Figure 9: Neptec's OPAL-360

Along with these hardware changes, significant 3D Real-time Intelligence (3DRi) software capabilities were developed to support large scale industrial automation through segmentation, object identification and tracking, and pose estimation [3]

3.2 Dust Penetration

Neptec has also developed a LiDAR technology that can penetrate significant amounts of obscurants, such as dust, smoke, fog etc. Obscurant penetration was developed in view of providing a true see-through capability for helicopter pilots in the final approach of a landing zone (LZ) in the desert (the “brownout” problem). The technical approach rests on these important elements: a high power pulsed laser emitter combined with a sensitive receiver, an optical design that rejects the backscattered light from nearby obscurant particles, a capability to extract target signals engulfed in a cloud of obscurants and an efficient filtering of noise caused by the reflection of light on obscurants. This capability was integrated into the OPAL-360 product.

The dust penetration capability has also shown benefits for using LiDAR in dusty industrial environments, such as open pit mining.

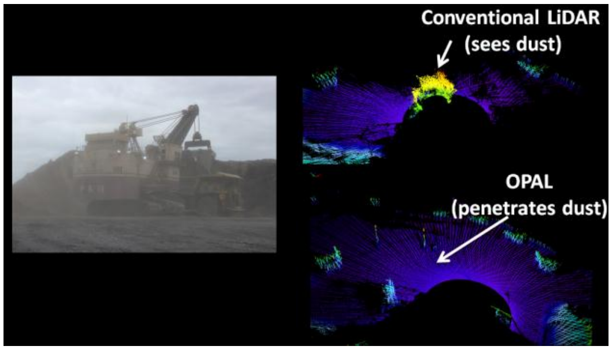

Figure 10: Scans from a bucket mounted OPAL 360 in conventional LiDAR mode and in obscurant penetrating mode.

Testing of this capability at Defense and Research Development Canada has shown that the OPAL dust penetration can see approximately 2 to 3 times the naked eye visibility ranges.[4]

This dust penetration capability has obvious advantages for dirty environments or helicopter landing scenarios but also shows promise for “spin-in” applications back to space. Neptec is working on several rover based applications for the moon and mars that could benefit from the ability to see effectively through dust, and is also working on Lunar landing LiDARs to perform navigation and hazard avoidance through the descent to the lunar surface. At a certain distance from the surface, a lander’s rocket plume disturbs the lunar regolith and could potentially obscure the landing site for the final 50m of descent for traditional LiDARs.

3.3 Different Scanning Geometry

While a 360º x 45º FOV is effective for many applications where the priority is to scan a large volume quickly, Neptec has also noted that other applications, such as helicopter landing or mobile vehicle applications, benefit from a “forward looking” sensor, with higher density of points concentrated over a smaller FOV. By modifying the OPAL-360 design to a more traditional Risley prism arrangement, NTC also developed the OPAL-120, shown along with its scan pattern in Figure 11.

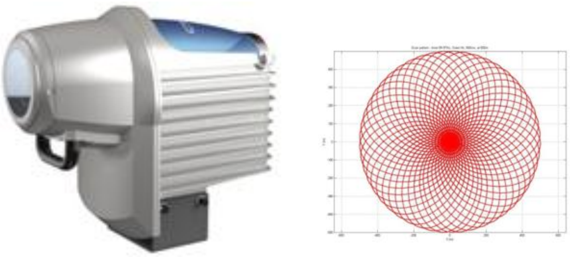

Figure 11: Neptec OPAL-120 and a 500ms Scan pattern

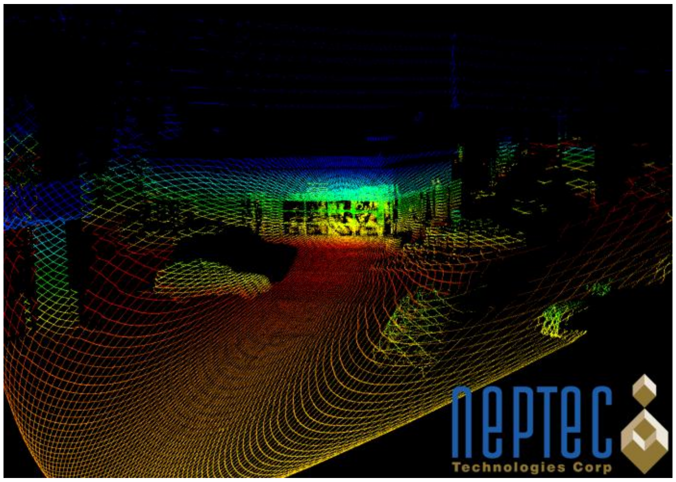

Figure 12 1s OPAL-120 Scan of a Tim Horton’s restaurant in Ottawa.

3.4 Acknowledgment

Neptec would like to thank the Canadian Space Agency for their financial support in the development of the IVIGMS (Contract 9F028-091395/001/MTB) and their support in testing at their Mars yard facility.

Neptec Technologies Corp. would like to thank Dr. Gilles Roy and Dr. Simon Roy from DRDC Valcartier. Part of this work was supported by DRDC Valcartier under contract W7701-10-3768 awarded to Neptec by Public Works and Government Services Canada.

4 Conclusions

Neptec developed a highly capable and innovative scanning LiDAR for the Canadian Space Agency. The sensor met the performance targets and demonstrated full 360 degree coverage that is well suited for rover applications

Due to the performance of the prototype sensor, the design was seen to be useful for several Earth based applications. A commercialization effort saw the successful development of the rover based prototype into a rugged and capable instrument for a wide variety of industrial applications. This commercialization included several improvements in the ruggedness, the integration of dust penetration capability, and the development of several 3DRi applications. These improvements show great promise for “spin-in” reapplication to future flight designs.

References

[1] Ruel, S.; C. English, M. Anctil, J. Daly, C. Smith, S. (2006). "Real-time 3D vision solution for on-orbit autonomous rendezvous and docking". Proc. SPIE 6220: 622009.

[2] Visscher, P. ; Jones, B, “Continued Development of Juno Rover” (2012) Proc. AIAA 50th, Aerospace sciences meeting; including the new horizons forum and aerospace exposition 2012

[3] E. Trickey, D.J. Lucifora, P. Wan, A. Scott “Enabling mine automation through the application of Neptec’s OPAL and 3DRi technology”, 2013 Proceedings of the 30th ISARC, Montréal, Canada, pp. 377-386

[4] Trickey, E., Church, P., Cao, X."Characterization of the OPAL obscurant penetrating LiDAR in various degraded visual environments” Proc. SPIE 6220: 622009.

Table 2: Scan pattern analysis

	Wedge: 90Hz Hut: 10Hz Time: 0.1s	Wedge: 101Hz. Hut: 1Hz. Time: 1s	Wedge:100.4Hz. Hut: 0.4Hz. Time: 2.5s	Wedge:100.2Hz. Hut: 0.2Hz. Time: 5s	Wedge:100.1Hz. Hut: 0.1Hz. Time: 10s	360 degree line scanner ‘specification’
Maximum Plane Distance [mm]	38504	6567	5686	5668	5702	11910
Mean plane Distance [mm]	2356	247	141	94	71	325.57
STD Plane Distance [mm]	4453	542	365	278	258	1164.8
Maximum Angle [mrad]	438	58.2	24.7	12.4	6.30	4.2
Mean Angle [mrad]	1742	12.2	5.24	2.98	1.84	3.2
STD Angle [mrad]	162	14.2	5.39	2.64	1.28	N/A
Sample Size	13400	134000	335000	670000	1340000	412715