Measurements and Analysis used for the Determination of the James Webb Space Telescope Integrated Science Instrument Module Vehicle Coordinate System

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ABSTRACT

A metrology survey was conducted by NASA Goddard Space Flight Center on the James Webb Space Telescope (JWST) Integrated Science Instruments Module (ISIM) Structure using 9 Laser Radar (LR) stations and 4 Laser Tracker (LT) stations. Using *Relationship Fitting* and the *Unified Spatial Metrology Network* (USMN) in Spatial Analyzer (SA), from New River Kinematics (NRK), it was possible to define a coordinate system for the telescope called the Vehicle Coordinate System (VCS) to an accuracy within 0.010 mm and 10 arc sec. Relationship fitting in SA was used to do a constrained global best-fit between the CAD model of ISIM and the corresponding LT- and LR-measured surfaces. This fitting process assures that the science instruments will be aligned in a way that simultaneously satisfies their individual alignment requirements. A total of 64 surfaces on four different types of ISIM interface features were used in the fit. After the VCS is established the tooling balls attached to the ISIM structure are valued with respect to the newly defined VCS. The metrology configuration and the SA analysis process used to establish the ISIM VCS will be explained. The role of data filtering and weighting on relationship fitting will also be discussed.

Keywords: Relationship fitting, Metrology, USMN, ISIM, JWST, VCS

1. INTRODUCTION

The James Webb Space Telescope (JWST), Figure 1, is comprised of three major elements: the Integrated Science Instrument Module (ISIM) Element, the Optical Telescope Element (OTE) and the Spacecraft (SC). The bare ISIM structure weighs 267 Kg and has dimensions of roughly 2 m x 2 m x 2 m. The ISIM structure provides mechanical interfaces and support for the three modular Science Instruments (SIs) and the Observatory Fine Guidance Sensor (FGS). The ISIM Element is integrated with the OTE as well as science processors, software, and other electronics.

The SIs are comprised of the Mid-Infrared Instrument (MIRI), which is being built by the European Space Agency (ESA) and a European Consortium of nations; the Near-Infrared Spectrometer (NIRSpec), which is being built by ESA and associated contractors; the Fine Guidance Sensor (FGS), which is being built by the Canadian Space Agency and their prime contractor; and the Near-Infrared Camera (NIRCam), which is being built for the University of Arizona by Lockheed Martin in Palo Alto, California.

The goals of the ISIM metrology and analysis were to establish the ISIM VCS using *Relationship Fitting* in SA and to verify that critical interface features on ISIM were fabricated and aligned to the required tolerance. The VCS has its origin at the vertex of the primary mirror surface in its deployed configuration. The nominal optical axis of the JWST telescope, also called the Optical Telescope Element (OTE), is the +V1 axis and is perpendicular to the tangent plane of the primary mirror at its vertex and points toward the secondary mirror. The +V3 axis points toward the single SMSS strut, such that the V1-V3 plane bisects the primary mirror along the primary mirror line of symmetry. The +V2 axis forms a right-handed system with the V1 and V3 axes. The V1-V2 plane also bisects the primary mirror along a line of symmetry formed by the segmented primary mirror boundaries.

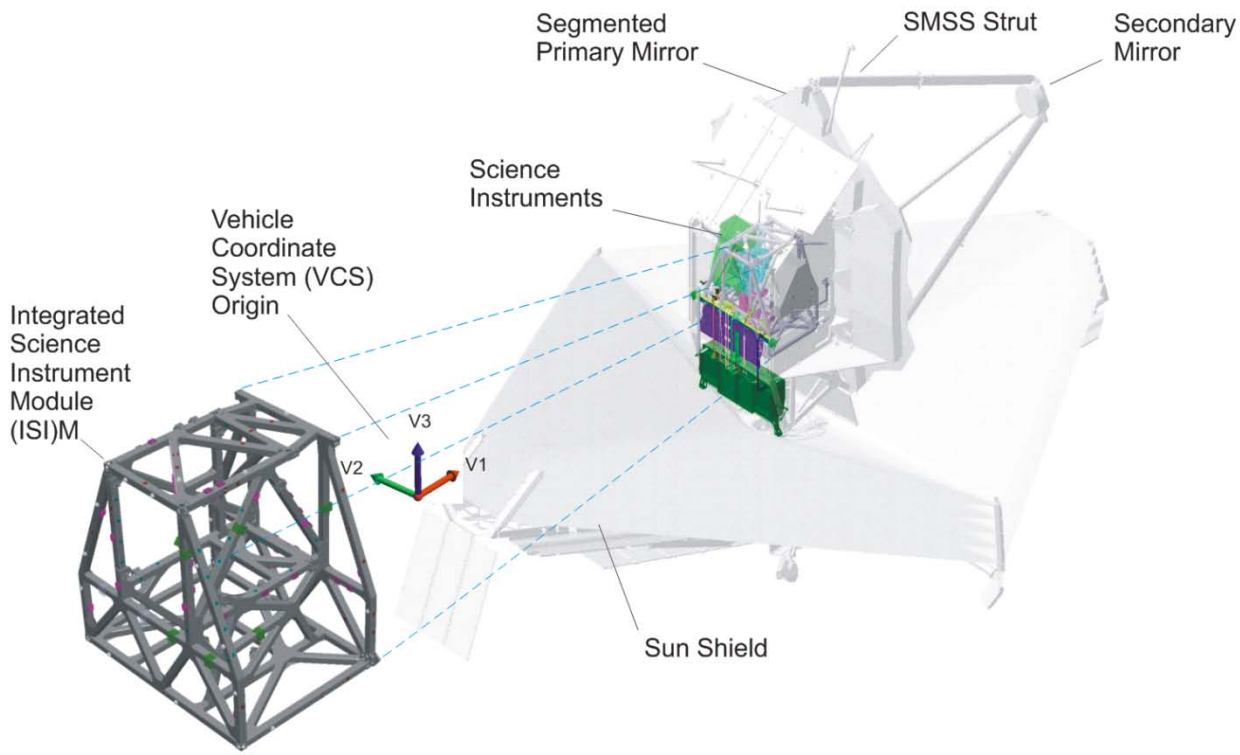


Figure 1 James Webb Space Telescope showing the location of the ISIM structure without the Science Instruments.

Determination of the best-fit Vehicle Coordinate System (VCS) will allow Science Instruments (SI) to be nominally positioned with respect to the ISIM Structure. There are Scientific Instrument Interface Plates (SIIP) attached to the SIs that provide a kinematic interface to the saddles on ISIM. These and other attachment interface features on the Structure were scanned using commercial Laser Radar (LR) and Laser Tracker (LT) systems. The Tooling Ball (TB) references, also called nest values, located on ISIM and the Handling Frame (HF) will be used to allow instruments used in future ambient and cryogenic metrology to tie back into the ISIM VCS.

The analysis of the of the ISIM metrology was done using Spatial Analyzer (SA), written by New River Kinematics (NRK). A method called *Relationship Fitting* was used in SA to bring all measured LR and LT data from the ISIM survey into rigid body alignment with the corresponding nominal design surfaces defined by a CAD model of ISIM. Relationship fitting is a very powerful metrology tool for data registration that extends beyond the traditional approach of best-fitting a few dozen tie points to their blueprint values to best-fitting a few thousand points to their blueprint values. *Relationship Fitting* provides increased measurement flexibility, since Spherically Mounted Retrospheres (SMR) or Tooling Balls (TB) are not required, as well as a potential for increased measurement accuracy resulting from the use of, effectively, an unlimited number of targets.

One of several requirements levied on ATK Aerospace by NASA Goddard Space Flight Center for the fabrication of ISIM was that all 64 interface surfaces, on 30 different parts, lie within a plane-parallel envelope located ±0.750 mm from the nominal design surface as measured at ambient temperature and pressure. The metric

$$D = |\text{Average}(S)| + 2*\text{StdDev}(S), \tag{1}$$

where $D < 0.750$ mm, and where S is the perpendicular point-to-plane distance for all points in the relationship, was used by NASA to establish if this requirement was met. The metric D was calculated from the values Average(S) and StdDev(S) reported by SA for each of the relationships.

2. ISIM METROLOGY SURVEY OVERVIEW

A metrology survey of ISIM and the HF was conducted in the Space Systems Development and Integration Facility (SSDIF) at NASA Goddard Space Flight Center using a Nikon MV224 Laser Radar (LR) and an M840 Leica Laser Tracker (LT). The mechanical configuration of ISIM, the Handling Frame (HF), and heavy-duty aluminum support tables are shown in Figure 2. There are six Kinematic Mount (KM) struts used to position ISIM with respect to the HF. The four corners of the HF were bolted to the support tables. Over the two week duration of testing in SSDIF the temperature ranged from 17.95 – 20.75 C, the relative humidity ranged from 45.1 – 54.5%, and the pressure ranged from 101.03 – 101.96 KPa.

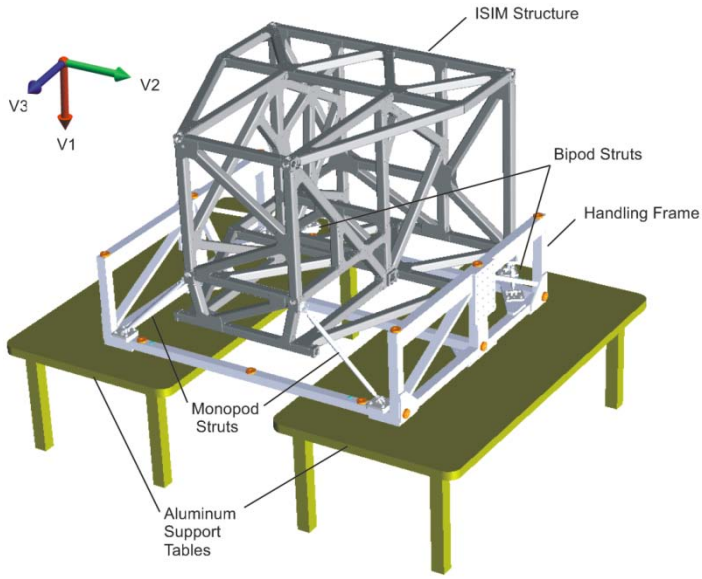


Figure 2. Metrology configuration for ISIM and HF on the aluminum support tables.

The metrology configuration, shown in Figure 3, used 9 sequential LR stations around the ISIM structure and 4 sequential LT stations. The height and position of each were adjusted to provide line of sight to the maximum number of interface features and TBs on ISIM. The LT was used at four different stations when line of sight could not be obtained with the LR.

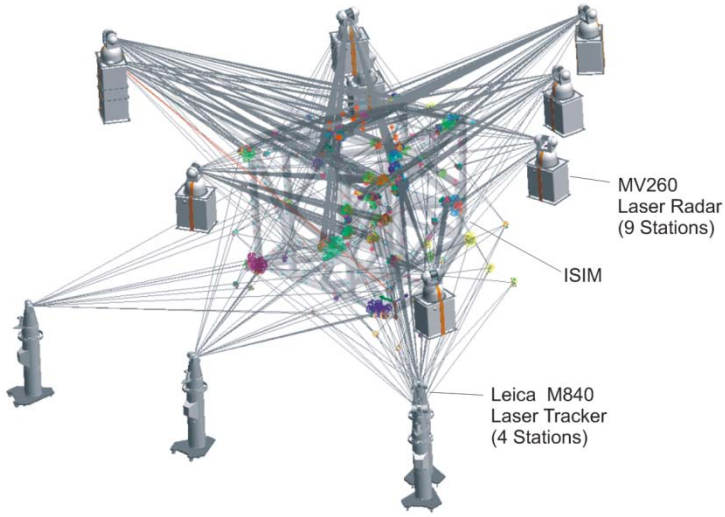
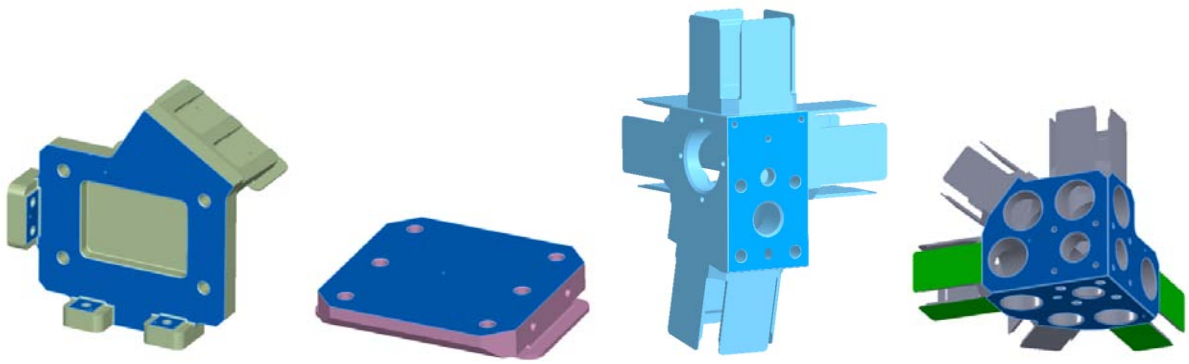


Figure 3. ISIM metrology survey showing shot lines from LR and LT stations.

The LR was bolted to a 2.5 m Brunson stand and the height of the LR head from the ground varied from 1.5 – 3 m. There were 45 composite ISIM TB values determined from a previous survey of ISIM. The LR- and LT-stations were coarsely tied-in to the VCS using a best-fit transformation between three measured 38.1 mm (1.5-inch) diameter TBs on ISIM and the corresponding composite nest values. The LR was used in *Auto-Measure* mode to measure all visible TBs on ISIM for five trials prior to any surface scans on ISIM. All visible interface surfaces of interest were then measured, provided that the angle of incidence of the LR beam did not exceed 60 degrees. Another 5 trials of LR measurements were made on the same TBs at the completion of the surface scans. When the LR did not have a line of sight to an interface features the LT was used to tram the surfaces with a 12.7 mm (0.5 inch) diameter SMRs attached to the end of a 150 mm post.

2.1 Target types

The ISIM VCS metrology survey involved the measurement of four different types of interface features on ISIM: saddles, platelets, monopods, and bipods, as shown in Figure 4. A total of 64 surfaces on 26 different parts on ISIM interface features were measured with the LR and LT as shown in Table 1. The three surfaces measured on all saddles were the base, short boss, and long boss, where the long boss consists of a split surface with two faces. The platelets, monopods, and bipods contained one surface each.



(a) (b) (c) (d)

Figure 4. The LR and LT surface measurements were made on: a) saddles, b) platelets, 3) monopod interfaces, and d) bipod interface. The *dissected* surface used in the *Relationship Fit* in SA is indicated by the blue highlighted surface.

Part Name	No. of Parts	No. of Surfaces per Part	Total No. of Surfaces
NiRSpec saddles	6	3	18
FGS saddles	6	3	18
NIRCam saddles	4	3	12
MIRI saddles	3	3	9
IATF platelets	3	1	3
Monopod Interface	2	1	2
Bipod Interface	2	1	2
TOTAL=	26		64

Table 1. Measured interface parts and surfaces on ISIM used in the *Relationship Fit* to establish the ISIM VCS.

3. JWST/ISIM VEHICLE COORDINATE SYSTEM ANALYSIS

The JWST ISIM VCS analysis consisted of bundling targets, eliminating outliers in surface scans, creating relationships, and *Relationship Fitting*. The bundling is used to bring all TB values and instruments into a best fit alignment. Spatial filtering is used to eliminate outliers above and below the measurement surface as well as around edges based on predefined tolerances. Relationships are then established between each of spatially filtered measurement surfaces and their corresponding CAD surfaces. The *Relationship Fit* determines the rigid body motion required to bring the measured data into alignment with the corresponding surfaces of the ISIM CAD model.

3.1 Bundling data from LR and LT stations

The SA files from each of the LT or LR station surveys were imported into a single SA file. Before running USMN it was necessary to eliminate all surface scan data from the USMN "Target/Point Selection" so that only TBs were used in the USMN. This is done by selecting the "Exclude Measurements" option in the USMN menu. Scanned surface points showed up in the *Target Selection* menu and had to be systematically excluded so that only TB values were used in the USMN. Exactly 1809 points were selectively excluded from the USMN. A check list was found to be essential for this process to guarantee that only the TB targets were used and not the surface scan points.

The TB target outliers were then eliminated using the *USMN Outlier Trimming* option if they exceeded a *Ranking Threshold* of 200%, where the *Ranking Threshold* shows the percentage of the expected 3-sigma envelope spanned by the measurement residuals. Since TB values with a rank greater than 200% have a high probability of being an outlier they were eliminated with the *USMN Outlier Trimming*.

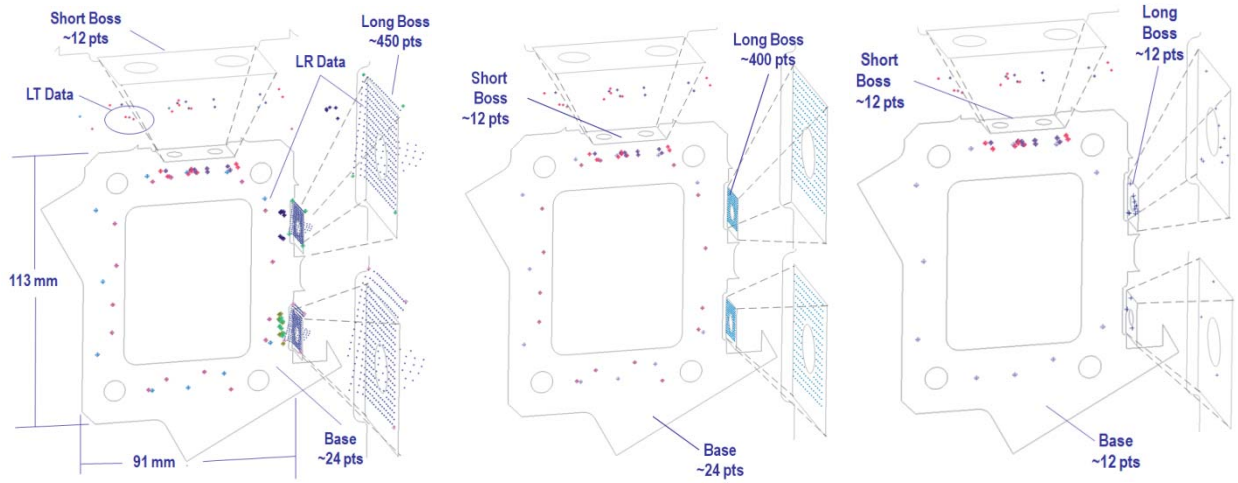
The *Overall 2 sigma RMS* from the USMN was 0.017 mm, and the *Average* was 0.013 mm. Composite values were generated in the USMN and an instrument association was manually created with the composite values. Typically it is not necessary to create an instrument association with the composite points, since this is often the last step in an analysis. However when relationship fitting is used, measurement points may be moved indirectly as a rigid body based on their instrument association.

3.1 Outlier elimination and thinning

The elimination of outliers in the measurement data prior to running a relationship fit was a critical step that had a significant impact on the global relationship fit result. In order to understand the nature of the spatial filtering that was required, some background on the particular measurement of the saddles will elucidate the problem.

An LR scan area was established by moving the focused LR beam to the corners of the scan box as viewed by a camera internal to the LR. When setting up the LR scan perimeter points it was difficult to define points that lie exactly within the boundary of the planar surface because of low image contrast and high LR beam obliquity angle. Consequently, this process generated a larger number of outlier points because the LR cloud data included measurements points that extended beyond the boundary of the planar surface, into holes, and onto the corner radii of the bosses.

Prior to eliminating outliers it was necessary to bring surface scan measurements on a particular part into alignment with the corresponding CAD representation of that part. The simplified CAD model of ISIM was imported into SA and surfaces to be used in the Relationship Fit were *Dissected* (i.e. a graphics primitive in SA representative of only the surfaces of interest on a CAD part to be used in the *Relationship Fit*). Relationships were established between the surface scan data and the corresponding dissected surface(s) using either *Point Cloud to Objects* or *Points to Objects*. The relationship was minimized using *Move Objects by Minimizing Relationship*. All data in the model moved as a rigid body during relationship optimization. Although the local relationship fit was mathematically minimized the resulting plane data was only coarsely aligned to the dissected CAD surface because of the large number of outliers. A manual rigid body adjustment was often necessary to bring the data within ±0.300 mm of the CAD surface. An additional local relationship fit iteration was used to bring the measured data with ±.050 mm of the CAD surface. Data thinning was performed during this final relationship fit to yield a maximum of 12 points per surface. Figure 5 shows the LR and LT measurement data on the saddle surfaces for the original data, after a local best-fit, and after thinning.



(a) (b) (c)

Figure 5. The LR and LT measured data on a saddle a) original measurements, b) after a local fit to part with outliers eliminated, c) after thinning to 12 points per surface.

Thinning was found to be necessary because the original data contained roughly 400 points on the saddle bosses and 12 points on the saddle bases. As a result of the disproportionate number of points per surface the relationship fit results for uniform weighting and normalized weighting were different by more than 0.500 mm. Consequently, it was decided that the best approach was to thin the number of points on all surfaces down to 12 points per surface. This effectively resulted in equivalent weights for both normalized and uniform weighting methods.

4. RESULTS

The ISIM VCS was successfully established using a combination of *USMN* and *Relationship Fitting* in SA. The rigid body change between the blueprint nest values and post-*Relationship Fit* nest values was ΔX=-0.268 mm, ΔY=0.005 mm, ΔZ=0.113 mm, $\Delta\theta x$ = 0.002 degrees, $\Delta\theta y$ = 0.002 degrees, and $\Delta\theta z$ = 0.002 degrees. The sensitivity in the minimum established by the Relationship Fit was characterized by observing the RMS of the global relationship fit while manually adjusting the relationship fit in position and orientation. Using this method, it was determined that translations were resolvable to better than 0.010 mm and rotations were resolvable to better than 10 arc seconds. The *Overall 2-sigma RMS* of 0.017 mm, determined from the USMN on the 45 TBs, must also be considered when tying back into the VCS, however.

The 45 TBs on ISIM and the HF were revalued in the ISIM VCS after the relationship fit was applied. These nests values will be used for future ambient and cryogenic metrology on ISIM to tie-in to the VCS. The bar chart in Figure 6 shows that the alignment requirement of D < 0.750 mm for all 64 surfaces was satisfied.

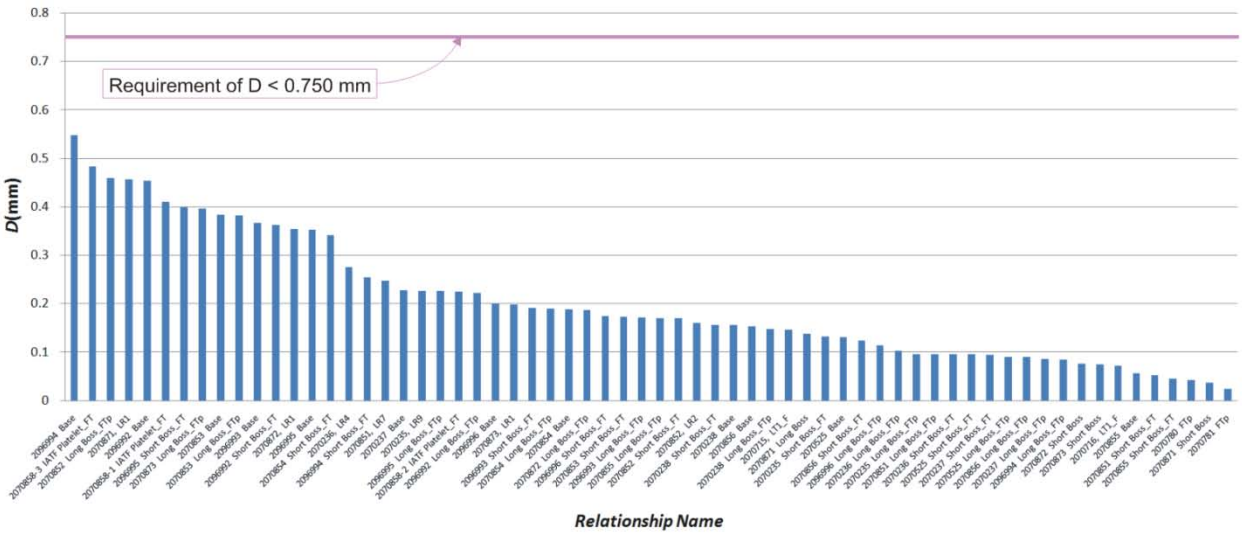


Figure 6. The requirement of D < 0.750 mm was satisfied for all 64 surfaces measured on ISIM after the *Relationship Fit*. Results have been sorted from highest to lowest D-values for clarity.

Some of the lessons learned when doing relationship fitting are as follows:

a) Design LT and LR measurements that will not require outlier elimination.

b) Avoid oblique scan angle with the LR since noise increases and sensitivity of picking perimeter points for LR scan boxes at oblique angles increases.

c) Minimize use of different instrument types like LT and LR. Using two or more instruments increases the analysis bookkeeping. Stick with one or the other instrument when possible.

d) An instrument association must be established when creating new clouds from filtered or thinned clouds. Failure to set-up an instrument association results in N-new filtered surfaces being created and irrecoverably left behind after a relationship fit.

e) Associate USMN composite points with an instrument so that when a *Relationship Fit* is done the composites move with the instruments. Often the USMN is the last step in an analysis and this would not have to be done. That is not that case, however, when *Relationship Fitting* is used.

f) Create a copy of the composite USMN points and do not assign an instrument association. These points will be left behind after running a *Relationship Fit*. A *Relationship Fit* can be reversed by transforming from composite points with an instrument association to the composite points without an instrument association.

g) A large number of relationships + a large number of points = high probability error in the final Relationship Fit, so use Measurement Plans (MPs) whenever possible in SA to minimize the number of manual steps.

h) Keep an Excel spreadsheet with the target names and relationships that should be included in the USMN and Relationship Fitting, respectively.

i) Using <F2> to explicitly select point groups. Selecting points and clouds graphically in files with a large number of points is error prone.

j) Create named views from the CAD model for each of the relationships.

k) Use an equal number of points per surface for all relationships. This minimizes differences between uniform and normalized weighting methods.

l) Manually move all data involved in a relationship fit using the *Move Manually* option in *Minimize Relationships*. Visually inspect graphical data to demine if any data did not move. If it did not, the data did not have an instrument association. Relationship RMSs that don't change after a *Manual Move* are another indication of an absent instrument association.

5. SUMMARY

The ISIM VCS was determined to high accuracy using a combination of *USMN* and *Relationship Fitting* in SA. *Relationship Fitting* to a large number of precision-machined surfaces is inherently more accurate than a metrology survey that relies solely on a USMN-only approach between the measured nest values and their nominal blueprint values. The use of a particular weighting method and the outlier rejection approach for surface scans should be carefully considered when planning a metrology survey, as both have the potential to significantly impact relationship fit results. Navigating through the many steps associated with *Relationship Fitting* on a large number of surfaces requires careful bookkeeping and attention to detail. Some of the manual steps in the process could be mitigated by using *Measurement Plans* (MP). Other steps, however, will require an added level of built-in software automation and error checking which are likely to evolve as the benefits of *Relationship Fitting* in the Metrology field are realized.

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