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ALIGNMENT WORKS IN ASSEMBLY, INTEGRATION AND TESTS OF COMMUNICATION SATELLITES

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ABSTRACT

The communication satellites have many pointing devices which their precise direction and location on the satellites have crucial importance on mission performance and control of the satellites. Typical pointing devices are antenna feed horns, feed assembly, antenna reflectors, reflector deployment and alignment mechanisms (RDAM), apogee kick engine (AKE), maneuver thrusters, sun sensors, star trackers etc. High accuracy of pointing direction requirements of these pointing devices necessitate the alignment works as critical during the assembly, integration and test (AIT) of the communication satellites. Errors in orientation of the pointing devices are evaluated and shown in the pointing budgets of the sub-system components. In this study, alignment works that are performed during AIT activities of the communication satellites and their sequence of practice are explained in details. Moreover, as part of those alignment processes, the shimming practice and calculation of shim thicknesses are also examined respectively.

INTRODUCTION

Alignment is a process of adjustment of parts and modulus to bring them to certain location and orientation with respect to reference axes in order to verify their design requirements. The pointing devices can be defined as the devices which its functionality and performance is directly depends on the location and orientation with respect to its attached body coordinate system. Spacecraft have many pointing devices onboard where their precise location and orientations with respect to satellite coordinate system affect mission quality and control of the satellite

There are number of subsystems having pointing devices on communication satellites such as attitude and orbit control subsystem (AOCS), propulsion subsystem(s) (PS), payload (P/L) and structure subsystems (SS) etc. Moreover, the scientific satellites and the observation satellites also have some optical instruments with special sensor devices requiring precise orientation to the localized areas. The communication satellites are orbiting in the geosynchronous orbit which is relatively the highest orbit above Earth to allow satellites to match Earth's rotation. Due to high orbit of communication satellites and need for sensitivity of the pointing devices to

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the distance increase. Orientation and localization of the payload and subsystems are optimized using the spacecraft reference axis.

The AOCS subsystem consisting many pointing devices such as star trackers, fine sun sensors (FSS), reaction/momentum wheels, earth sensors. Propulsion system consists of main apogee kick engine (AKE) and number of small maneuver thrusters. Communication payload includes many antennas with feed horns, feed assembly, sub-reflectors, reflector deployment and alignment mechanism (RDAM). All of these devices and sensors have to be precisely and rigidly placed and oriented. The Figure 1 shows a typical communication satellite with many direction and orientation sensitive pointing devices.

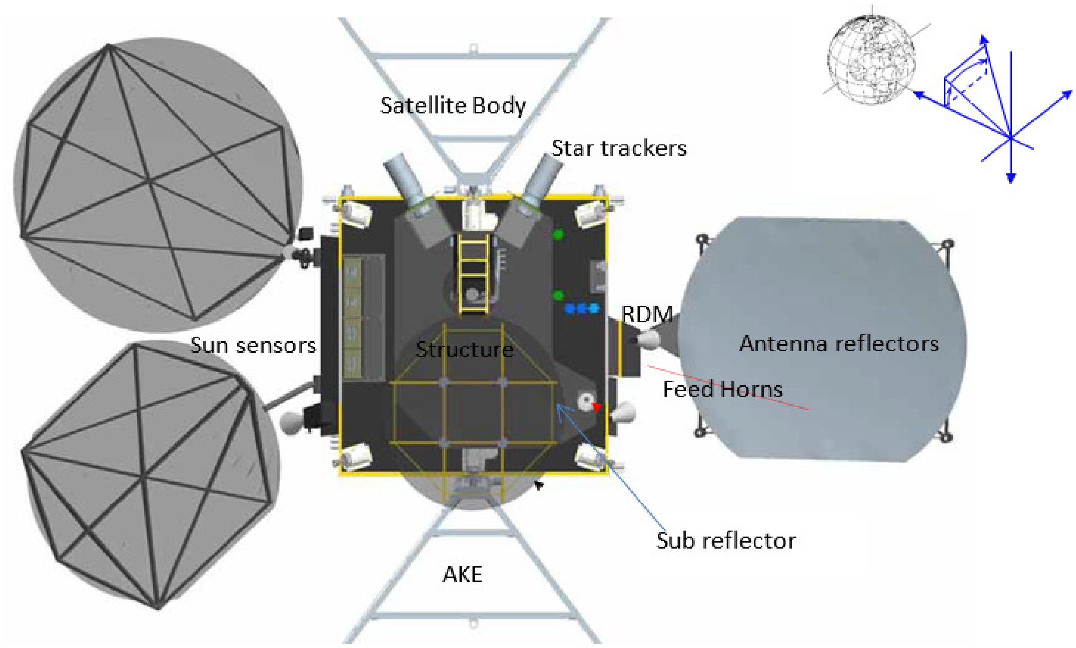


Figure 1: A typical communication satellite with many pointing devices

The mission quality of the spacecraft is mainly affected by the precise alignment accuracy of these pointing devices [Sahin and Kahriman, 2014, Hetherington et.al 2013]. For example, misalignment of the maneuver thrusters causes high propulsion fuel consumption and reduces spacecraft mission life. Similarly, if apogee kick engine (AKE) is not correctly aligned it causes over consumption of propellants and reduces satellite life duration. The misalignment of the antenna pointing devices causes decrease in ground RF performance, interference problems, less coverage area than the proposed mission area etc. For example, misalignment of antenna orientation of geosynchronous communication satellite by 1/100º causes approximately 6 km drift at 36000 km orbit. (1/100° = 6km /36000km). The Figure 2 shows a typical shift error due to misalignment of a payload antenna orientation on a communication satellite.

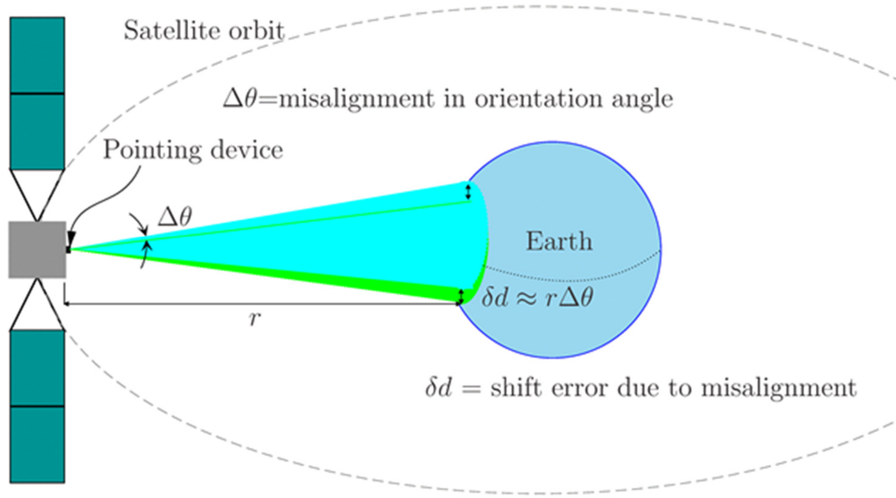


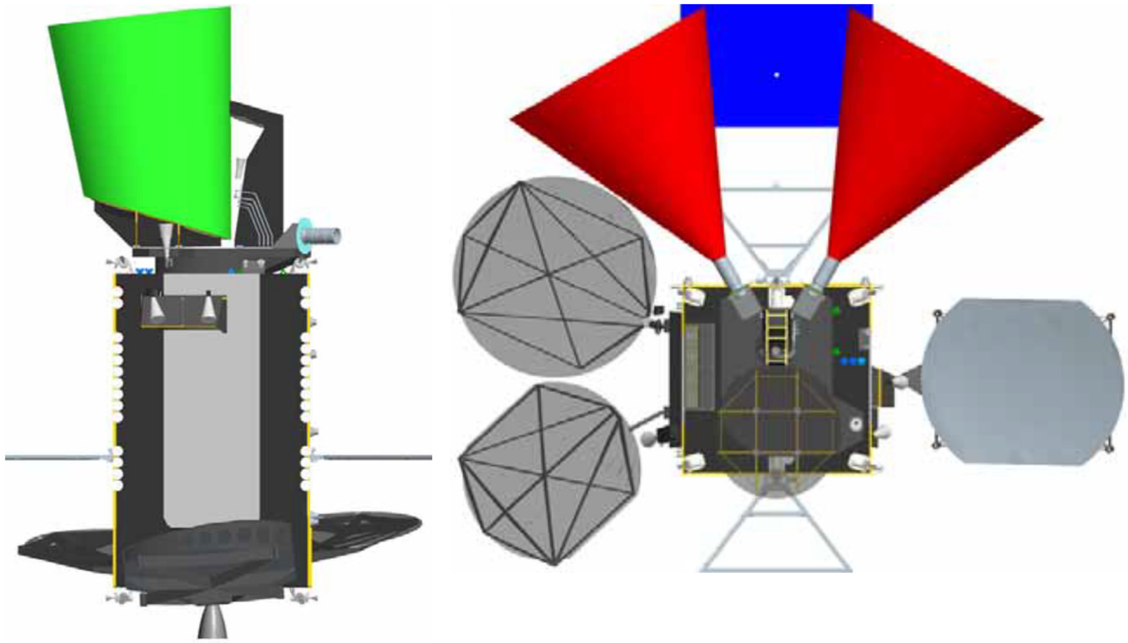
Figure 2: Typical pointing error due to misalignment of pointing device

All possible pointing errors due to sensor sensitivity, assembly, integration errors, operation conditions, orbital factors, short and long term environmental effects are determined and evaluated to find the limits of the errors. The pointing errors are evaluated during design and updated after the tests of satellites. The maximum permissible levels of errors for performance parameters are prescribed and/or set as technical performance requirements. In order to meet these requirements pointing errors budgets are prepared and results are compared with the requirements. In system budget documents, the pointing errors of all pointing devices and their components are listed in details. Total combined errors are compared with previously determined performance requirements. Summation of all error effects of a pointing device is done by linear and/or statistical combination rules such as root sum square (RSS). A typical antenna pointing error values for a reflector of 1600 mm diameter and a focal length of 1200mm. are shown on the Table 1

Table 1: A typical example antenna pointing error budget table (All values in deg.)

Antenna Pointing Error	**Roll**	**Pitch**	**Yaw**
S/C Reference Accuracy	0,0095	0,0095	0,0072
Reflector Position Measurement	0,0024	0,0024	0,0036
Feed Position Measurement	0,0024	0,0024	0,0
Feed and Reflector Misalignment	0,0095	0,0095	0,0072
S/C Axes Orientation Uncertainty	0,0048	0,0041	0,0036
Lateral Error due to Reflector Rotation	0,0024	0,0	0,0
Uncertainty of Range Orientation	0,0045	0,0045	0,0045
Face to face measurement error	0,001	0,001	0,001
Uncertainty of RF Boresight determination	0,003	0,003	0,003
RSS Value	**0,016**	**0,015**	**0,012**

Graphical analysis of field of views of these pointing devices are also done to assure that no any conflict will occur during the service life of the spacecraft. The Figure 3 shows a field of view analysis of a communication satellite. The red and green colored cones on the figures show the field of views of the antenna and the star trackers.



a) b)

Figure 3: The field of views of a) A payload antenna b) Star trackers

In addition to the spacecraft pointing devices, various subsections of spacecraft such as support panels, support brackets, mount parts assembly and integration works require precise alignment measurements and adjustments. All these works are precisely conducted onto the rigid manufacturing fixtures then followed by their precise orientation inspection before shipment to final integration site in order to ensure that the pointing devices and related subassemblies are properly mated. Their connections must also free from abnormal stresses as well as their measured values fall within a tolerable range. Alignment measurements are done by using mirror or an optical alignment cube that mounted rigidly to the pointing devices or their components.

The alignment measurements are performed before and after the environmental tests. On ground, the spacecraft undergoes some environmental and functional tests to demonstrate the spacecraft conformity with respect to performance requirements. Major structural issues during tests are endurance and thermos-elastic structural stability of the satellite during the tests. Thus, It is crucially important to perform equipment stability measurements during various phases of the AIT.

The structural integrity and thermos-elastic deformations can be evaluated via using 3-D coordinate measurement systems and comparing pre- and post-test alignment measurements. Optical and/or laser coordinate measurement systems are used for 3-D coordinate measurements. The orientation angle measurements can be done using optical measurement systems. Some measurement systems use fixed rotary table as reference system. On this system, the satellite is located on a calibrated alignment rotary table with an adapter. Instruments used for spacecraft alignment are industrial theodolite systems which use auto-collimation method (See the Figure 4). For alignment tests, the satellite is set on the rotary table via an adapter or placed an appropriate location on a specific mechanical ground support equipment (MGSE). Alignment is optically measured using an alignment cube attached to the satellite or equipment by collimating with a theodolite. When the measured value does not fall within a tolerable range, adjustment is done by inserting shims and measurement are repeated to bring measured value to the requirement. Initial alignment data is used as baseline data for evaluating possible deformation. Alignment measurement is repeated after the thermal and otjer environmental tests. This measurement is conducted in order to verify that variations between the data obtained after the thermal environmental test and the baseline data measured at initial alignment are within tolerance.

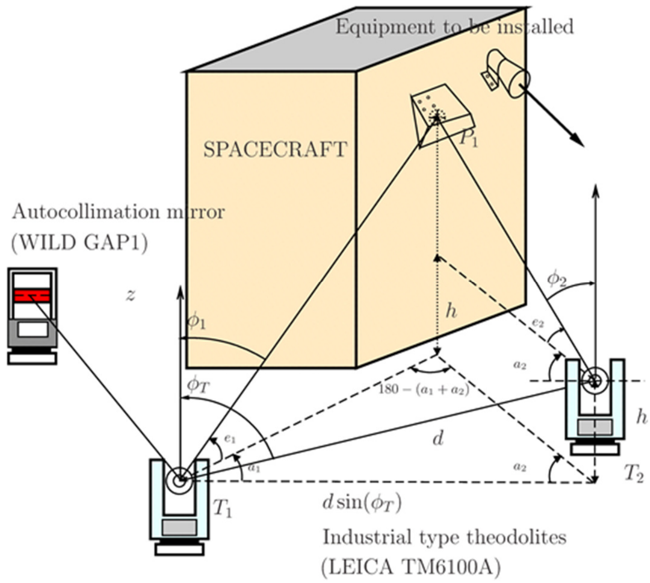


Figure 4: Typical optical coordinate measurement system with theodolites

Final alignment measurement is conducted in order to do final propellant thruster head adjustment as a result of Physical Mass Properties Test. All these tests may result in some misalignments and relative residual gaps. Therefore; shimming may be required to fix these misalignments and gaps, and their assembly & integration. From initial installation to the final checks, the shimming may be required to bring the pointing devices to their precise orientation and localization with respect to satellite reference coordinate system. In the following section mathematical bases and formulation to determine the necessary shimming thicknesses at the supports of the pointing devices and/or their supporting panels to bring them to required design orientations are presented. The Table 2 shows list of typical pointing devices of a communication satellite. The Table 3 shows all alignment measurements during the assembly and integration of a communication satellite.

Table 2: Typical pointing devices of a communication satellite

Subsystem	**Sensors**
Attitude and Orbit Control System (AOCS)	Fine Sun sensor Earth sensor Star tracker
Propulsion system	Maneuver thrusters AKE Apogee Kick Engine Electric propulsion thrusters
Payload	Antenna Feed Assembly RADM Antenna subreflectors Antenna reflectors Antenna subreflector towers
Structure	Satellite main body Subassembly of subsystems Structural panels North and South Payload Panel mating

Table 3 Alignment measurements during the assembly and integration

Step	Phase	Notes
1	Subsystem Manufacturing	During Subsystem manufacturing
2	Structure system Integration	Initial installation measurement
3	Subsystem integration to spacecraft	Alignment and dimension measurement
4	Post TVAC test alignment measurement	Align. meas. after the TVAC test
6	Post Dynamic test alignment measurement	Align. meas. after the Dynamic test
,7	Other subsystem integration to S/C	Some subsystems after TVAC tests
7	Final alignment	Final
8	Other alignment	If necessary
9	Mass distribution alignment	If necessary

3-D coordinates the assembly mating points can be measured by various methods. There are mainly three methods for 3-D coordinate measurements in industrial coordinate measurement works. The first one is electronic coordinate measurement system (ECMS) method and it is generally used for assembly and manufacturing process. In this method two theodolites and a autocollimation mirror are used to determine coordinates and the functional axis of the equipment with respect to the reference system of the spacecraft axis. Theodolites sights are performed on mirror cubes defining a local optical reference for sight interface. The measured coordinates are transformed to the satellite global coordinate system by rotation transformation matrix. The second one is laser tracking or scanning method and this method is becoming more popular since it is more precise and requires less labor than the ECMS method. The third one is video-grammetry method in which three-dimensional coordinates of points on an object are determined by measurements made in two or more video images taken from different angles. The video-grammetry is more suitable for distortion analysis of complex objects under thermal or mechanical stress.

A proposed method for shimming calculations in alignment process

The method is based on shimmed surface and required (design) normal vector have to be parallel i.e. cross product of these two vectors has to be zero. The equations to determine the shimming thickness, results in 2 or 3 linear equations depending upon the shimming directions can be solved analytically. Example application is given for 3-D shimming calculations.

Mathematical basis for shimming calculations are based on parallelism of two vectors in three-dimensional coordinate system. If two vectors are in parallel, then dot-product of two vectors has to be zero vector. Vectors for this product are required design orientation vector and measured vector from the alignment measurements plus the shimming vector. In mathematical derivations, the following assumptions will be assumed for the sake of simplicity.

1. Only z-coordinates of the points under consideration are changed by installing shims.
2. Length, outer diameter and height of the shims do not affect the orientation, i.e. shims are assumed to be point or geometry of the shims do not affect the x and y coordinates of the connection surface
3. To make relative minimal shimming, only changes in z-coordinate displacements of two points are allowed.
4. The design normal vector is transformed to and pointing device coordinates system to simplify the solution i.e. they are on the same coordinate system.

Pretend that the required design orientation is given as normal vector to surface as

$$\boldsymbol{R} = r_x\boldsymbol{i} + r_y\boldsymbol{j} + r_z\boldsymbol{k} \tag{1}$$

Alternatively, the required orientation can be given in terms of horizontal angle (H) and vertical angle (V) and coordinate system between spherical coordinate system to Cartesian coordinate system (see Appendix)

$$\boldsymbol{R} = r_x\boldsymbol{i} + r_y\boldsymbol{j} + r_z\boldsymbol{k} = r\sin(V)\sin(H)\,\boldsymbol{i} + r\sin(V) \tag{2}$$

Where *r* can be taken arbitrarily, say *r =1* since only the orientation is concerned. If necessary, coordinate transformation can be done and relation between the old and new coordinate system can be related as

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} \quad (3)$$

For example, angular rotation θ about the z-axis and following rotation β about x-axis result in the following new coordinates

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\beta) & \sin(\beta) \\ 0 & -\sin(\beta) & \cos(\beta) \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} \quad (4)$$

The pointing device has a plane defined by a normal. The plane normal is obtained by three points on the plane**.** The normal of the pointing device before the shimming is defined as ***N.***

$$\boldsymbol{N} = \boldsymbol{r_{21}} \times \mathbf{r_{31}} = (y_{21}z_{31} - y_{31}z_{21})\boldsymbol{i} + (z_{21}x_{31} - z_{31}x_{21})\boldsymbol{j} + (x_{21}y_{31} - x_{31}y_{21})\boldsymbol{k} \quad (5)$$

But this orientation is misaligned and yet to be changed to bring it to the required orientation. This can be done by shimming of the points. Let assume that point-2 ant point-3 on the device are shimmed in z-direction by the amounts of $\Delta z_2 \; and \; \Delta z_3$. All the rest of connection points rather than point-2 and point-3 on the device also have to be brought to this even position accordingly by shimming process. The new orientation is obtained by shimming. The shimming is done adding or removing some shim layers in z-direction only. After the shimming process, the new orientation is changed and its new normal vector ***N'*** becomes

$$\boldsymbol{N}' = (y_{21}z'_{31} - y_{31}z'_{21})\boldsymbol{i} + (z'_{21}x_{31} - z'_{31}x_{21})\boldsymbol{j} + (x_{21}y_{31} - x_{31}y_{21})\boldsymbol{k} \quad (6)$$

where $z'_{31} = z_{31} + \Delta z_3$ and $z'_{21} = z_{21} + \Delta z_2$. Then the new plane orientation **N'** must be parallel to the required orientation, i.e. the cross product of these vectors must be equal to zero

$$\begin{aligned} \boldsymbol{R} \times \boldsymbol{N}' = \boldsymbol{0} = & \left[(x_{21}y_{31} - x_{31}y_{21})r_y - (z'_{21}x_{31} - z'_{31}x_{21})r_z\right]\boldsymbol{i} \\ & + \left[(y_{21}z'_{31} - y_{31}z'_{21})r_z - r_x(x_{21}y_{31} - x_{31}y_{21})\right]\mathbf{j} \\ & + \left[(z'_{21}x_{31} - z'_{31}x_{21})r_x - (y_{21}z'_{31} - y_{31}z'_{21})r_y\right]\boldsymbol{k} \end{aligned} \quad (7)$$

Each component of the vector has to be equal to zero and they result in the following linear system of equations

$$\begin{bmatrix} x_{31} & -x_{21} \\ -y_{31} & y_{21} \end{bmatrix} \begin{bmatrix} z'_{21} \\ z'_{31} \end{bmatrix} = \frac{(x_{21}y_{31} - x_{31}y_{21})}{r_{\boldsymbol{z}}} \begin{bmatrix} r_y \\ r_x \end{bmatrix} \quad (8)$$

where $z'_{21}$and z'_{31} are unknowns and they can be solved as

$$\begin{bmatrix} z'_{21} \\ z'_{31} \end{bmatrix} = -\frac{1}{r_z} \begin{bmatrix} r_x x_{21} + r_y y_{21} \\ r_x x_{31} + r_y y_{31} \end{bmatrix} = -\frac{1}{r_z} \begin{bmatrix} x_{21} & y_{21} \\ x_{31} & y_{31} \end{bmatrix} \begin{bmatrix} r_x \\ r_y \end{bmatrix} \quad (9)$$

The shim thicknesses of the connection points can be found as

$$\begin{bmatrix} \Delta z_2 \\ \Delta z_3 \end{bmatrix} = \begin{bmatrix} z'_{21} - z_{21} \\ z'_{31} - z_{31} \end{bmatrix} = -\begin{bmatrix} x_{21} & y_{21} & z_{z1} \\ x_{31} & y_{31} & z_{31} \end{bmatrix} \begin{bmatrix} \left(\frac{r_x}{r_z}\right) \\ \left(\frac{r_y}{r_z}\right) \\ 1 \end{bmatrix} = -\tan(V) \begin{bmatrix} x_{21} & y_{21} & z_{z1} \\ x_{31} & y_{31} & z_{31} \end{bmatrix} \begin{bmatrix} \cos(H) \\ \sin(H) \\ \left(\frac{1}{\tan(V)}\right) \end{bmatrix} \quad (10)$$

References

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