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International Space Station Remote Sensing Pointing Analysis

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INTERNATIONAL SPACE STATION REMOTE SENSING POINTING ANALYSIS

by

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B.S. Electrical Engineering, South Dakota School of Mines and Technology, 1982

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Mechanical, Materials, and Aerospace Engineering
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ABSTRACT

This paper analyzes the geometric and disturbance aspects of utilizing the International Space Station for remote sensing of earth targets. The proposed instrument is SHORE (Station High-Sensitivity Ocean Research Experiment), a multi-band optical spectrometer with 15 m pixel resolution. The analysis investigates the contribution of the error effects to the quality of data collected by the instrument.

The analysis begins with the discussion of the coordinate systems involved and then conversion from the target coordinate system to the instrument coordinate system. Next the geometry of remote observations from the Space Station is investigated including the effects of the instrument location in Space Station and the effects of the line of sight to the target. The disturbance and error environment on Space Station is discussed covering factors contributing to drift and jitter, accuracy of pointing data and target and instrument accuracies. Finally, there is a brief discussion of image processing to address any post error correction options.

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TABLE OF CONTENTS

LIST OF FIGURES	viii
LIST OF TABLES	ix
LIST OF ACRONYMS	x
CHAPTER 1: INTRODUCTION	1
SHORE Overview	1
ISS Remote Sensing Overview	2
Literature Research Review	3
Analysis Approach	4
Definitions	5
SHORE Requirements	5
CHAPTER 2: COORDINATE SYSTEMS	8
Target Coordinate System	8
Space Station Inertial Coordinate System	9
Local Orbital Coordinate System	10
Space Station Body-Fixed Coordinate System	11
U.S. Laboratory Module Coordinate System	12
ISPR Body-Fixed Coordinate System	13
WOLF Coordinate System	14
SHORE Coordinate System	15
CHAPTER 3: COORDINATE TRANSFORMATION	17
Transformation Approach	18
CHAPTER 4: OBSERVATION GEOMETRY	20

Window Angles and Effects	21
Geodetic Effects.....	24
Imaging Angle Effects	25
Pixel Smear	26
CHAPTER 5: ISS POINTING KNOWLEDGE	28
Accuracy of ISS GN&C Data	28
Positional Accuracy	29
Velocity Accuracy	29
Attitude Accuracy	30
Timing Accuracy	30
Conclusion	31
CHAPTER 6: ISS Disturbances.....	32
Effects of Disturbances	33
CHAPTER 7: IMAGE PROCESSING.....	34
CONCLUSION.....	36
Analysis Results.....	37
APPENDIX: COORDINATE TRANSFORMATION CALCULATIONS	39
LIST OF REFERENCES	53

LIST OF FIGURES

Figure 1: Target Coordinate System.	9
Figure 2: Space Station Inertial Coordinate System.	10
Figure 3: Local Orbital Coordinate System.	11
Figure 4: Space Station Body-Fixed Coordinate System.	12
Figure 5: U.S. Laboratory Module Coordinate System.	13
Figure 6: ISPR Body-Fixed Coordinate System.	14
Figure 7: WORF Coordinate System.	15
Figure 8: SHORE Coordinate System.	16
Figure 9: Geometry Angles.	17
Figure 10: Observation Geometry.	20
Figure 11: Space Station Window Transmittance.	23
Figure 12: Space Station Window Angle of Incidence Transmittance.	24
Figure 13: Geodetic Effects	25
Figure 14: Image Angle Effects.	26
Figure 15: Image Processing Flow Diagram.	35

LIST OF TABLES

Table 1: SHORE Requirements vs. ISS Characteristics 38

LIST OF ACRONYMS

BAD	Broadcast Ancillary Data
CCD	Charge Coupled Device
FEM	Finite Element Method
FOR	Field Of Regard
FOV	Field Of View
FSRI	Florida Space Research Institute
GN&C	Guidance, Navigation and Control
GPS	Global Positioning System
ISPR	International Space Station Program Rack
ISS	International Space Station
WORF	Window Observation Research Facility
LOS	Line Of Sight
RSS	Root Sum Squared
SHORE	Station High-Sensitivity Ocean Research Experiment
SIGI	Space Integrated GPS Inertial Navigation System
SSP	Space Station Program

CHAPTER 1: INTRODUCTION

This paper provides an analysis of the factors affecting a remote sensing optical spectrometer flying on the International Space Station (ISS). The instrument is the Station High-Sensitivity Ocean Research Experiment (SHORE). The analysis considers the geometric and disturbance factors and errors affecting the quality of image capture using the SHORE instrument. SHORE targets consist of coral reefs, atolls, tidal areas and shore/ocean interfaces. These targets present a difficult subject to image due to the high reflectivity of the land and the low reflectivity of the water. SHORE's high dynamic range provides a high sensitivity capability well suited to targets of this type.

SHORE Overview

The SHORE instrument is planned to be a multi-band optical spectrometer covering the 390 through 1000 nm wavelengths in multiple (potentially 16 to 25) bands. SHORE would provide high dynamic range due to the ability to assign multiple detector pixels to each filter band and to repeatedly image the same points on the target. The SHORE instrument would be mounted within the Window Observational Research Facility (WORF) that is located within the U. S. Laboratory module in ISS.

The SHORE imager would be a CCD type detector. The CCD window will be covered with an interference filter array. The filter array consists of multiple optical bands covering rows of detector pixels in length and varying pixels wide. Widths of spectral bands are selected based on the characteristics of the signal at the wavelength involved.

The efforts to date have focused on a SHORE prototype instrument. The goals are to characterize and quantify the performance of this approach. The data collected it will provide the necessary information to decide if pursuing a flight instrument is reasonable and what the specific technical requirements and science goals would be practical. The SHORE prototype is based on a 1920 x 1080 CCD array with 12.5 micro-meter pixels, a frame rate of up to at least 30 frames per second and 12 bit resolution per pixel. This specification drives many of the quantities utilized in this paper.

ISS Remote Sensing Overview

ISS provides unique capabilities as a remote sensing platform. The orbital period of 90 minutes provides frequent passes over 58% of the earth's surface. The orbital inclination of 51.7 degrees allows target access up to 52.7 degrees in latitude. Based on the targets identified by the science team, ISS orbits pass over targets multiple times within reasonable periods to allow effective revisits of identified sites.

ISS also provides an orbital observing location and environment that allows development and testing of instruments without the risk and cost burden of free flying platforms. Instruments can be designed and operated more easily on ISS in the pressurized and temperature controlled environment alleviating the problems associated with direct exposure to space. Additionally, due to the repetitive access to ISS, instruments can be returned to earth for modification, new instruments can be carried up to test new technologies and techniques, and on orbit adjustments and modification can be performed by the crew and impromptu/adhoc images can be taken. The instrument can be operated remotely with no crew involvement or crew attendance if necessary.

The disadvantage of flying on ISS includes: disturbance rich environment relative to free fliers, physical limits on size, weight, power, cooling; resource contention, additional requirements for flying in a man rated system. However, for multiple classes of instruments, ISS offers significant advantages.

Literature Research Review

Early in the planning and operation of ISS, multiple analyses looked at the environment in terms of instruments requiring pointing. The following papers addressed ISS pointing topics:

- “Medium accuracy pointing system for attached payloads”.
- “Conceptual design of pointing control systems for Space Station gimbaled payloads”.
- “Coupled Space Station Freedom/Payload Point System dynamic analysis employing modal significant criteria”.
- “Statistical analysis of Space Station Freedom/Payload Pointing System structures and controls interaction”.
- “Pointing Terminology/Definitions”.
- “A pointing system design concept for Space Station attached payloads”.

Also many papers are available that discuss the issues associated with remote sensing pointing. The papers listed below were helpful in understanding many of the issues and topics.

- “Propagation of angular errors in two-axis rotation systems”.
- “Integrated modeling and analysis methodology for precision pointing applications”.
- “Monte Carlo analysis of satellite beam pointing errors”.

- “Application of Square-Root Filtering for Spacecraft Attitude Control”.
- “Optical pointing stability achievement through isolation”.
- “Pointing and jitter control for the Eclipse mission”.
- “Statistics for spacecraft pointing and measurement error budgets”.
- “Quaternion feedback for spacecraft large angle maneuvers”.

The references cite related papers and previous studies. This paper looks at specific application of a SHORE type instrument and uses the U. S. Laboratory window aboard ISS in the pressurized environment. This is the unique aspect of this paper.

Analysis Approach

The analysis starts with coordinate systems and angle transformation; geometry aspects of imaging targets from ISS; then looks at disturbances in terms of contribution to errors and the significance to SHORE. The conclusion summarizes the effects of the factors and the evaluation against the SHORE requirements.

1. Collect and define: Key Definitions, Requirements and Coordinate Systems.
2. Analyze Coordinate Transformations.
3. Analyze Observation Geometries.
4. Investigate ISS Pointing Knowledge.
5. Analyze Disturbance Models.
6. Image Processing Factors.
7. Summarize Conclusions.

Definitions

The following are the key definitions¹ affecting SHORE.

- Absolute pointing accuracy - Total angle difference between actual pointing direction and the desired pointing direction.
- Relative pointing accuracy - Variation of total angle between the actual pointing direction and the desired pointing direction over a time interval required to acquire an image.
- Jitter - RMS image motion on the time scale of a single exposure.
- Drift - Average motion during time to capture a complete image data set.

SHORE Requirements

The SHORE project science goals set the instrument pixel resolution, jitter, drift, pointing accuracy and the absolute real time pointing knowledge requirements. These requirements drive a FOV of 2.5 degrees, pixel smear and image size of 16 km square. The SHORE specifications are described below.

- A SHORE pixel size of 15m was selected to provide the best resolution trade off of science objectives against exposure time, pointing errors and system costs.

¹ White Paper "Pointing Terminology/Definitions"

- The FOV is based on the pixel size and the number of pixels cross track and along track. A 15 m pixel size determines the SHORE FOV to be 2.5 degrees.
- Absolute pointing accuracy is the total angle difference between actual pointing direction and the desired pointing direction. SHORE requires less than 1/4 of FOV (4 km) absolute pointing accuracy. Absolute pointing accuracy will be determined by the accumulated effect of all the errors. (i.e. GN&C measurement accuracy, time accuracy, disturbances, geometric distortions). Target size is a factor to consider in this specification. Smaller targets will easily fit within the FOV of SHORE while large targets may have difficulty as they approach the limits of the FOV experiencing the greatest error levels.
- Relative pointing accuracy is the variation of the total angle between the actual pointing direction and the desired pointing direction over the time interval required to acquire an image (90 s). Jitter and drift are the two values used to quantify the effects.
- Jitter is defined as RMS image motion on the time scale of a single exposure (31.7ms = 31.5 Hz). The SHORE specification calls for less than 1/2 of a pixel variation due to jitter. SHORE pixels are 15m therefore the variation must be < 7.5 m, equating to a jitter of < 20 micro-radians.
- Drift is defined as average motion of the Line of Sight (LOS) during time to capture a complete image data set (90 s). The SHORE specification calls for less than 1/4 of a pixel (3.75 m) drift over the imaging period, equating to a drift of < 10 micro-radians.

- SHORE timing accuracy is based on the minimum smear a pixel will experience during exposure due to the relative velocity between the instrument FOV and the target. Average satellite sub-point speed is 7.25 km/s, the SHORE requirement is for less than $\frac{1}{4}$ FOV variation. This translates to a timing accuracy of < 0.55 seconds.

CHAPTER 2: COORDINATE SYSTEMS

This section describes the coordinate systems used from the target all the way through to the SHORE instrument. The Space Station utilizes several coordinate systems to support multiple geometric relationships. The coordinate systems discussed are: target, Space Station inertial, Space Station orbital, Space Station body-fixed, U.S. Laboratory, ISPR, WOLF, SHORE.

The first coordinate system provides the target location specified in longitude and latitude. Each sequential coordinate system is described in the order from target to SHORE detector. The target, Space Station inertial, Space Station orbital, Space Station body-fixed, U.S. laboratory and ISPR coordinate systems are from Space Station documentation².

Target Coordinate System

The target coordinate system provides geodetic longitude and latitude location data based on the ellipsoidal model of the earth.

² Diagrams in the following 6 sections are taken from SSP 30219 Space Station Reference Coordinate Systems, Revision F, 26 October 2001.

Figure 1: Target Coordinate System.

The ellipsoidal model accounts for distortions due to the non-spherical earth shape. Longitude is measured from the prime (Greenwich) meridian to target meridian. Latitude is measured from the plane of the Earth's true equator to the target latitude.

Space Station Inertial Coordinate System

The Space Station inertial coordinate system provides inertial coordinates of the ISS center of mass based on the J2000 celestial coordinate system (earth center of gravity and Aries mean of 2000).

Figure 2: Space Station Inertial Coordinate System.

The coordinate system is earth centered, inertial and right handed. The X axis points to mean vernal equinox of epoch (2000 January 1). The Z axis is directed along earth axis of rotation. The Y axis completes the right handed system with the X-Y plane located at Earth's mean equator of epoch.

Local Orbital Coordinate System

The Space Station local orbital coordinate system provides reference coordinates in the local orbital vertical and horizontal directions.

Figure 3: Local Orbital Coordinate System.

The origin is located at the Space Station center of mass, the X-Z plane is in the instantaneous orbital plane, the Z axis is located along the radius to the center of the earth, the Y axis is normal to the orbital plane, and the X axis completes the right handed orthogonal Cartesian system.

Space Station Body-Fixed Coordinate System

The Space Station body-fixed coordinate system provides reference coordinates based on the axes defined for the entire Space Station structure.

Figure 4: Space Station Body-Fixed Coordinate System.

The origin is located at the Space Station center of mass. The X axis is parallel with the laboratory module center line. The Y axis is parallel with the starboard truss axis. The Z axis completes the orthogonal system and is typically pointed in the NADIR direction. Pitch, roll and yaw angles are defined in relation to the local orbital coordinate system.

U.S. Laboratory Module Coordinate System

The U.S. laboratory coordinate system provides reference coordinates based on the axes defined for the pressurized module containing WOLF and SHORE.

Figure 5: U.S. Laboratory Module Coordinate System.

The origin is located 1000 inches forward of the aft trunnion center line. The X axis is located along the geometric center line of the laboratory module. The Z axis is parallel to the line perpendicular with the X axis and through the center line of the keel pin. The Y axis completes the right handed system.

ISPR Body-Fixed Coordinate System

The ISPR body-fixed rack coordinate system provides reference coordinates based on the axes defined for the racks mounted within the laboratory module.

Figure 6: ISPR Body-Fixed Coordinate System.

The origin is located at the interface of the centerline bushing attachment at the left front side of the rack. The X axis is in line with the center line of the attachment bushing. The Y axis is parallel with the plane of the rack floor. The Z axis completes the right handed system.

WORF Coordinate System

The WORF coordinate system provides reference coordinates for the WORF mounted experiments and equipment³.

³ WORF coordinate system taken from SSP52000-PIH-WRP, Volume III. WORF Rack Interface Definition Document, October 3, 2003, Revision B.

Figure 7: WOLF Coordinate System.

The origin is located at the center of the payload support shelf. The X axis is parallel to the support shelf center line located along the left to right center of the rack. The Y axis is parallel to the center line from the front to rear of the rack. The Z axis completes the right hand system.

SHORE Coordinate System

The SHORE coordinate system provides coordinates based on the axes defined for the instrument.

Figure 8: SHORE Coordinate System.

The origin is located at the center of rotation for the instrument elevation (cross track pointing) axis and the azimuth (along track pointing for nodding) axis. The X axis is the LOS, the Y axis is the elevation axis, the Z axis is the azimuth axis.

CHAPTER 3: COORDINATE TRANSFORMATION

This chapter describes the Euler angle transformations to translate the target geodetic latitude and longitude to SHORE azimuth and elevation. The discussion describes the approach, steps performed and the benefits and shortcomings. The figure below depicts the geometry and angles involved in viewing a target.

Figure 9: Geometry Angles.

Transformation Approach

Target latitude and longitude is the starting point, the final output are the SHORE azimuth and elevation angles. See Appendix A for details of the calculations. The approach uses vectors and transformation matrices in a 6-step process to perform the transformations.

1. The target latitude and longitude in addition to the Greenwich Mean Sidereal Time are used to create a vector $\mathbf{T}_{IJK}$ from the center of the earth to the center of the target in the IJK earth centered inertial coordinate system.
2. The ISS position vector $\mathbf{R}_{VEC}$ is known (provided as IJK components in a GN&C measurement). Using vector calculations, the vector $\mathbf{V}_{IJK}$ is obtained. $\mathbf{V}_{IJK}$ points from the center of the target to the center of mass of ISS (end point of $\mathbf{R}_{VEC}$).
3. The first coordinate transformation uses the inclination, longitude of the ascending node, argument of perigee and the true anomaly (calculated from time, $\mathbf{R}_{VEC}$ and $\mathbf{V}_{VEC}$ or potentially provided in a GN&C measurement) resulting in $\mathbf{V}_{IJK}$ expressed in terms of the ISS local orbital coordinate system.
4. The second coordinate transformation incorporates ISS attitude (roll, pitch, yaw; provided in GN&C measurements) to convert $\mathbf{V}_{IJK}$ from the ISS local orbital coordinate system to the body-fixed coordinate system ($\mathbf{V}_{Lo}$).
5. $\mathbf{V}_{SS}$ is a fixed vector in the ISS body-fixed coordinate system from the ISS center of gravity to the center of rotation of SHORE. A vector calculation is again performed with

vector $\mathbf{V}_{LO}$ and $\mathbf{V}_{SS}$ creating the $\mathbf{T}_{SHOREIo}$ vector pointing from the SHORE center of rotation in the body-fixed coordinate system to the center of the target. It is coincident with the desired SHORE line of sight.

6. The final coordinate conversion is performed to express $\mathbf{T}_{SHOREIo}$ in the SHORE (azimuth and elevation) coordinate system ($\mathbf{T}_{SHORE}$).

This approach provides the line of sight coordinates for SHORE to point at the target center. It uses simple vector operations in addition to typical Euler angle transformations. It does not require spherical geometry or approximations. Applying quaternions to this problem would be an interesting exercise. Shortening the number of calculations would be an improvement. This approach could easily be coded in software and the needs of SHORE do not drive stringent real-time requirements. However an in-depth error analysis has not been done to understand any error effects inherent in the approach. The model was developed in Mathcad which is very flexible and a good tool for this task. However, errors continue to surface in the model results and it is unclear if these are resolution artifacts or a problem in the model implementation.

CHAPTER 4: OBSERVATION GEOMETRY

The analysis of SHORE observations from Space Station include window angles and effects, geodetic effects, imaging angle effects and pixel smear. The figure below shows the overall observation geometry.

Figure 10: Observation Geometry.

This analysis uses a Space Station mean altitude of 386 km⁴, an inclination of 51.7 degrees and an orbital period is approximately 90 minutes. This provides SHORE image access to 58% of the earth's surface. The inclination and window FOV allows SHORE to image to a maximum latitude of 52.7 degrees north and south. Based in a previous study⁵, targets⁶ are available for imaging as frequently as 3 per orbit when within range to access images.

The WOLF working group and the SHORE science team determined that the window in Space Station provides a Field of Regard (FOR) of 30 degree half angle. SHORE operates within the FOR with a 2.5 degree Field of View (FOV). SHORE will require an azimuth/elevation pointing capability. The pointing system allows SHORE to acquire targets within the window FOR and to slew the camera to provide the required relative target motion to capture the image compensating for effects of the ISS orbital velocity.

Window Angles and Effects

At a Space Station average altitude of 386 km the window FOR provides targets within a radius of 436 km from the instantaneous satellite sub-track point. The SHORE azimuth (along track) and elevation (cross track) pointing capabilities allow imaging of targets within this 436 km window FOV.

⁴ From: <http://spaceflight.nasa.gov/realdata/sightings/help.html>; 386 kilometers (240 miles).

⁵ SHORE Memo "Target frequency study".

⁶ SHORE Target Book.

The Space Station window is located in the US Laboratory Module, facing in the nadir direction. The window is 20 inches in diameter, composed of 3 panes combining to a total thickness of 2.9 inches. The window optical characteristics are described by figures 11 and 12⁷. SHORE operates in the visible spectrum from 390 nm to 1000 nm. From the window optical characteristics for transmittance in figure 11, it can be seen that the SHORE spectrum is largely passed by the window in a transmittance range of 0.93 to 0.98 for the wavelengths between 442 and 868 nm. Below 442 nm at 412 nm the transmittance drops to approximately 0.75. SHORE calibration and characterization will compensate for this reduction in transmittance values. Additional window data shows transmittance above approximately 0.85 out to 1000 nm at the longer wavelengths.

⁷ US Laboratory Nadir Window Radiometric Calibration. Dean Eppler SAIC/ISS Payloads Office.

Figure 11: Space Station Window Transmittance.

Figure 12 shows window transmittance as a function of viewing angle. SHORE will look through the window at angles up to 30 degrees. The SHORE wavelengths of interest between 442 and 868 nm pass through the window at 0.87 to 0.98 transmittances for the full 30 degree viewing angle range. Below 442 nm at 413 nm the transmittance varies from 0.72 to 0.87. Again, SHORE calibrations and characterization will allow correction of the angular effects of the window transmittance.

Figure 12: Space Station Window Angle of Incidence Transmittance.

SHORE placement in WOLF would locate the lens opening as close as possible to the window. Additionally, an optimized pointing system would provide a center of rotation at the opening of the lens, minimizing the distance the center of the lens moves from the center of the window. This pointing approach maximizes the quality of SHORE viewing through the window. However, the approach may increase the effect of disturbances due to the SHORE center of mass and center of rotation not being co-located.

Geodetic Effects

Geodetic effects can distort images due to the non-planar image field.

Figure 13: Geodetic Effects

Figure 13 provides a diagram to understand the effects involved. Due to the small pixel dimensions of SHORE and the magnitude of the geodetic effects, the distortion is minimal for SHORE. For instruments with much larger fields of view the geodetic effects become significant.

Imaging Angle Effects

The geometry of observations from ISS distort the target image. The geometric effects cause pixel dimensional variations due to cross track and along track angles. Figure 14 illustrates the dimensional variation due to off nadir pointing angles.

Figure 14: Image Angle Effects

The distortion is greatest at the edges of the window FOR (full 30 degree half angle). The pixels become 12.5% longer in the radial direction outward from the satellite sub-point. For 15 m pixels used by SHORE this adds 1.9 m.

Pixel Smear

Pixel smear occurs due to the relative motion of the target during the individual frame integration times. For shorter integration times, smear is reduced while longer integration times increase smear. The SHORE specification calls for less than a full pixel of smear. This equates to one pixel (15 m) moving one full pixel distance (another 15 m) during the frame integration time. The smear is compensated for during data processing where the image is re-sampled to include all

photons received from the ground element 15 m wide by 15 m+smear long into one 15 m x 15 m element. Smearing reduces the image resolution in the along track direction.

The SHORE integration time is 1/30 of a second (33 ms). During this time the instantaneous line of sight of SHORE is required to move less than 15 m. This results in a line of sight velocity of 454.5 m/s. The pointing system to be used by SHORE and ISS pointing knowledge will be required to provide adequate accuracy and resolution to meet the specification.

CHAPTER 5: ISS POINTING KNOWLEDGE

This chapter analyzes the ISS position, velocity, attitude and time measurements that SHORE would use for pointing and image acquisition. SHORE pointing requirements are the current resolutions and accuracies set for the prototype SHORE instrument. The values may change as instrument development progresses. The accuracy and resolution of these measurements are considered based on the SHORE requirements.

Accuracy of ISS GN&C Data

ISS provides on board measurements accessible to experiments that indicate the orbital location, velocity, attitude and time. These measurements will be used by SHORE to point the instrument at targets and acquire images. The accuracy of the ISS measurements affect the quality of SHORE pointing and image acquisition. The measurements used are: position and velocity vectors in IJK components based on the geocentric inertial J2000 reference system; roll, pitch and yaw ISS attitude angles; and GPS time. These measurements are distributed using Broadcast Ancillary Data (BAD) packets. The BAD packets are cyclically distributed in a synchronous protocol.

The position and time measurements are relative to the GPS antenna locations, not the ISS center of gravity. The conversion from the GPS antenna coordinate system to the ISS center of gravity is anticipated to be insignificant. This topic in addition to several others would be investigated following the approval for construction of a flight instrument.

Positional Accuracy

The positional measurements provide SHORE the basic orbital position information. The early ISS program requirements for position vector accuracy called for a probability of 99.73 percent that the RSS error would be less than 914 m. The R4 release of GN&C software greatly improves the accuracy to less than 6 m per axis.

Accuracy in the position vector affects SHORE pointing by translating the announced position some delta from the actual position. The translational errors create a bias/offset effect of the line of sight of SHORE as it is moved along the IJK axes. An error of 6 m creates an equivalent bias/offset error of 6 m at the target for the error components perpendicular to the SHORE line of sight. The SHORE requirement of absolute pointing accuracy calls for less than $\frac{1}{4}$ the FOV. This equates to 4 km. The positional error is well within the SHORE requirement. The error component along the SHORE line of sight has a negligible affect on the image.

Velocity Accuracy

The velocity measurement provides SHORE the orbital velocity information. The early ISS program requirements for velocity called for on-orbit translational state knowledge with a semi-major axis error less than 1000 feet (305 meters) 3-sigma. The R4 release of GN&C software improves the accuracy of coasting flight accuracy to less than 20 meters.

Accuracy in the velocity vector affects pixel smear. The velocity errors create variation in the relative velocity of the line of sight and the target. An error of 20 m creates a variation in the slewing velocity of the 454.5 m/s required rate. The SHORE requirement calls for less than 15 m of smear (one pixel). As long as the pointing system used by SHORE can provide a slewing velocity of 434.5 m/s, the requirement can be met.

Attitude Accuracy

Initial ISS attitude determination was accurate to within 0.25 degrees. SIGI firmware improved the accuracy to 0.1 degrees per axis. During more extreme maneuvers and events (docking, momentum wheel dump, etc.), attitude variations will exceed this accuracy. However, the more significant events are planned and can therefore be addressed in SHORE operational scheduling.

The effect of the accuracy of the attitude measurements manifests as rotational errors in SHORE pointing. These errors are more problematic due to the long distances and small FOV of SHORE. A 0.1 degree rotation error in an attitude axis equates approximately to a similar 0.1 degree error in SHORE pointing. The SHORE specification for absolute pointing accuracy calls for less than $\frac{1}{4}$ the FOV. The SHORE FOV is 2.5 degrees, therefore any attitude variation less than 0.625 degrees meets the requirement.

Timing Accuracy

ISS time is based on GPS time. Accuracy following the SIGI firmware update is within 20-50 microseconds. Collection and distribution of time in BAD packets are delayed due to routing. The delay could be in the range of 2 seconds. It has not been determined what the characteristics are of the variability in this distribution delay.

The effect of time errors could be a significant factor for SHORE. The satellite sub-point is moving at 7.25 km/s, the SHORE requirement is for less than $\frac{1}{4}$ the FOV variation. To meet the SHORE requirement, time must be accurate to not less than 0.55 seconds. The time distribution delay will need to be characterized to fully analyze this aspect.

Conclusion

The ISS orbital state measurement knowledge meets the SHORE requirements with a yet to be determined effect of the time distribution delay. The position, velocity and attitude services meet the SHORE requirements with margin. The accumulative effects of the errors have not been assessed. A more detailed analysis would characterize the over all effect of the errors.

CHAPTER 6: ISS Disturbances

Space Station has many disturbance sources ranging from large (i.e. docking, momentum wheel dumps, re-boost) to small (i.e. crew push-offs, vent valve cycling, CMG noise). The larger disturbances are usually known in advance and can be planned into the SHORE operations schedule. The smaller disturbances may occur with out prior knowledge.

The disturbance environment is characterized by models and on board accelerometer measurements. There are two models available; an overall ISS model and the WOLF model. The WOLF model is build upon the ISS model therefore incorporating the overall ISS disturbance environment. The WOLF model is a NASTRAN dynamic FEM model providing modal frequency data from 0.1 to 300 Hz. The model is built utilizing 20,900 nodes and 23,600 elements. The large ISS model is complex and involved. It aggregates hundreds of disturbance sources into response frequencies up to 50 Hz. It is fortunate that instrument developers can utilize the WOLF model to keep the analysis task manageable.

The WOLF model allows the analysis of different instrument designs and the resulting disturbance results. Since SHORE is in the prototype stage and a physical design is not available, the FEM capabilities of the model were not used in this analysis. The WOLF model also provides disturbance data for instruments positioned on the optical bench. The disturbances at the WOLF optical bench are on the order of 19 micro-radians in each axis. This is the data used for this analysis applied to the SHORE prototype.

The accelerometer measurements are collected in the U.S. Laboratory Module, the same module in which WOLF is located. The accelerometer data has been collected over a substantial

period and would likely be utilized in the analysis for an approved flight instrument development. A detailed analysis has not been performed to compare the models and accelerometer data.

Effects of Disturbances

The disturbance levels of 19 micro-radians have the effect of adding an angular component of error to the SHORE pointing. The rotational error component offsets the azimuth and elevation pointing. The SHORE requirements for relative pointing stability include jitter and drift. The jitter requirement is for less than $\frac{1}{4}$ a pixel during the integration period (33 ms). The drift requirement is for less than $\frac{1}{4}$ a pixel during the image acquisition period (90 s).

The angle subtended by a 15 m pixel seen from SHORE at a height of 386 km is 40 micro-radians. At a disturbance level of 19 micro-radians, it's almost half a pixel. SHORE will incorporate passive damping into the design of a flight instrument. A reduction of at least 2 in jitter is expected with the passive damping. The contribution of errors by the disturbances is a key factor in the SHORE design. Passive damping is the goal of the instrument due to the considerable increase in cost and complexity accompanying active damping systems. The drift requirement is expected to be acceptable due to the apparent drift stability of ISS and measurement knowledge.

CHAPTER 7: IMAGE PROCESSING

A high level description of data processing is included in this analysis. The author did not undertake detailed investigation into approaches and requirements for processing SHORE images. Other SHORE team members addressed image process for the prototype. The topic is included here for completeness and to highlight the corrections image processing is expected to provide to improve the final SHORE data products.

The SHORE instrument produces a considerable quantity of data for each image. One frame of the CCD sensor is acquired every 33 ms for 90 seconds. Depending on the spatial resolution and pixel resolution of the sensor, the ‘data cubes’ can be large. The image processing must accept the data cube as input and produce one frame of the entire image for each spectral band.

Other functions performed during image processing are flat field normalization, dark image correction and pixel re-sampling. The flat field and dark image corrections are typical functions performed on image data. The pixel re-sampling is required to correct for the smear resulting from the motion of the LOS across the image during each frame integration period. The ability to re-sample the data and move energy back into a single pixel will help improve the image quality.

After these image processing tasks are complete, there will likely be additional levels of processing specified by the science user depending the types of information desired and research to be accomplished. Image processing will also support operational calibrations, instrument health checks and determining instrument ageing characteristics. Figure 15 depicts the flow diagram for

the image processing for the SHORE prototype. An IDL program using ENVI is used to implement the image processing.

Figure 15: Image Processing Flow Diagram.

CONCLUSION

This paper investigated and analyzed the topics related to using the International Space Station for a remote sensing platform for a SHORE type instrument. The requirements for the prototype SHORE instrument were used as the basis of analysis. The SHORE requirements are:

- A SHORE pixel size of 15m was selected to provide the best resolution trade off of science objectives against exposure time, pointing errors and system costs.
- The FOV is based on the pixel size and the number of pixels cross track and along track. A 15 m pixel size determines the SHORE FOV to be 2.5 degrees.
- Absolute pointing accuracy is the total angle difference between actual pointing direction and the desired pointing direction. SHORE requires less than 1/4 of FOV (4 km) absolute pointing accuracy. Absolute pointing accuracy will be determined by the accumulated effect of all the errors. (i.e. GN&C measurement accuracy, time accuracy, disturbances, geometric distortions). Target size is a factor to consider in this specification. Smaller targets will easily fit within the FOV of SHORE while large targets may have difficulty as they approach the limits of the FOV experiencing the greatest error levels.
- Relative pointing accuracy is the variation of the total angle between the actual pointing direction and the desired pointing direction over the time interval required to acquire an image (90 s). Jitter and drift are the two values used to quantify the effects.

- Jitter is defined as RMS image motion on the time scale of a single exposure (31.7ms = 31.5 Hz). The SHORE specification calls for less than 1/2 of a pixel variation due to jitter. SHORE pixels are 15m therefore the variation must be < 7.5 m, equating to a jitter of < 20 micro-radians.
- Drift is defined as average motion of the LOS during time to capture a complete image data set (90 s). The SHORE specification calls for less than 1/4 of a pixel (3.75 m) drift over the imaging period, equating to a drift of < 10 micro-radians.
- SHORE timing accuracy is based on the minimum smear a pixel will experience during exposure due to the relative velocity between the instrument FOV and the target. Average satellite sub-point speed is 7.25 km/s, the SHORE requirement is for less than 1/4 FOV variation. This translates to a timing accuracy of < 0.55 seconds.

Analysis Results

The analysis shows promise for SHORE observations from ISS. The delay in time measurement routing is an open issue that will need to be resolved. The results from this analysis support continued work to develop the prototype. However, the areas investigated in this paper are a subset of a full analysis required for developing an instrument capable of performing in space.

The table below summarizes the requirements against the effects analyzed. Color coding is used to indicate the areas where requirements are met (green) and where there is an issue (yellow) or an inability to meet (red) the requirements.

Table 1: SHORE Requirements vs. ISS Characteristics

Effects Requirements	Window Optical Characterization	Geodetic Effects	Viewing Angles	ISS Measurement Knowledge	Disturbance
Absolute Pointing Accuracy < 4 km				Position & Attitude	
				Time Delay	
Jitter < 7.5 m (33 ms)					Passive Damping (> 30 Hz)
Drift < 3.75 m (90 s)				Position, Attitude, Time	90 s
Pixel Smear < 15 m				Position, Attitude, Time	
15 m Pixel		Shape Distortion	Dimension Distortion		
Spectral Range 390 – 1000 nm	Transmittance Losses				

APPENDIX: COORDINATE TRANSFORMATION CALCULATIONS

Determines the pointing of the vector from SHORE to center of target. Starts with target location (vector T_{IJK}) in latitude and longitude, position and velocity vectors and the date and time. See fig. 1 for overall diagram.

 Constants:

$$\begin{aligned} R_{\text{earth}} &:= 20925644.0288713 && \text{Radius in feet.} && \mu &:= 14076441746610709.60 && \text{Earth's mass.} \\ e_{\text{earth}} &:= 0.081819221456 && \text{Earth's Eccentricity (geodetic)} \end{aligned}$$

Mathcad Note: $:=$ is assignment statement. $=$ is display statement. (Shows actual value of variable).

 Initial Values:

$$\text{Target Latitude and Longitude:} \quad \text{lat} := 1.975 \quad \text{long} := -90.082$$

$$\text{Position Vector in feet:} \quad R_I := -1.8990 \cdot 10^7 \quad R_J := -1.1251 \cdot 10^7 \quad R_K := 5.8920 \cdot 10^5$$

$$R_{\text{vec}} := \begin{bmatrix} R_I & R_J & R_K \end{bmatrix} \quad R_{\text{vec}} = \begin{pmatrix} -1.899 \times 10^7 & -1.125 \times 10^7 & 5.892 \times 10^5 \end{pmatrix}$$

$$R_{\text{vecmag}} := \sqrt{[R_{\text{vec}(1,1)}]^2 + [R_{\text{vec}(1,2)}]^2 + [R_{\text{vec}(1,3)}]^2} \quad R_{\text{vecmag}} = 2.208 \times 10^7$$

$$\text{Velocity Vector in feet/sec:} \quad V_I := 8.4479 \cdot 10^3 \quad V_J := -1.3221 \cdot 10^4 \quad V_K := 1.9799 \cdot 10^4$$

$$V_{\text{vec}} := \begin{bmatrix} V_I & V_J & V_K \end{bmatrix} \quad V_{\text{vec}} = \begin{pmatrix} 8.448 \times 10^3 & -1.322 \times 10^4 & 1.98 \times 10^4 \end{pmatrix}$$

$$V := \sqrt{[V_{\text{vec}(1,1)}]^2 + [V_{\text{vec}(1,2)}]^2 + [V_{\text{vec}(1,3)}]^2} \quad V = 2.526 \times 10^4$$

$$\text{Date and Time:} \quad \text{Mo} := 11 \quad \text{d} := 14 \quad \text{yr} := 2005 \quad \text{h}_{\text{UTC}} := 16 \quad \text{minits} := 28 \quad \text{scnds} := 4$$

$$\text{Orbital Elements:} \quad \text{incl} := 51.647 \quad \text{ascendingnode} := 209.435 \quad \text{argptruea} := 0 + 1.95$$

Calculating Orbital Elements:

$$H := R_{\text{vec}}^T \times V_{\text{vec}}^T \quad H = \begin{pmatrix} -2.15 \times 10^{11} \\ 3.81 \times 10^{11} \\ 3.461 \times 10^{11} \end{pmatrix}$$

$$h := \sqrt{[H_{(1,1)}]^2 + [H_{(2,1)}]^2 + [H_{(3,1)}]^2} \quad h = 5.578 \times 10^{11}$$

$$n := \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \times H \quad n = \begin{pmatrix} -3.81 \times 10^{11} \\ -2.15 \times 10^{11} \\ 0 \end{pmatrix}$$

$$n_{\text{mag}} := \sqrt{[n_{(1,1)}]^2 + [n_{(2,1)}]^2 + [n_{(3,1)}]^2}$$

$$e_{\text{vec}} := \frac{\left(V^2 - \frac{\mu}{R_{\text{vecmag}}} \right) \cdot R_{\text{vec}}^T - \left(R_{\text{vec}}^T \cdot V_{\text{vec}}^T \right) \cdot V_{\text{vec}}^T}{\mu}$$

$$e_{\text{vec}} = \begin{pmatrix} -8.829 \times 10^{-4} \\ -5.368 \times 10^{-4} \\ 4.247 \times 10^{-5} \end{pmatrix} \quad e_{\text{mag}} := \sqrt{[e_{\text{vec}(1,1)}]^2 + [e_{\text{vec}(2,1)}]^2 + [e_{\text{vec}(3,1)}]^2}$$

$$e_{\text{mag}} = 1.034 \times 10^{-3}$$

$$\xi := \frac{V^2}{2} - \frac{\mu}{R_{\text{vecmag}}}$$

$$\xi = -3.184 \times 10^8$$

$$\text{inc}_{\text{calc}} := \arccos \left[\frac{H_{(3,1)}}{h} \right] \cdot \frac{180}{\pi} \quad \text{inc}_{\text{calc}} = 51.647$$

$$\Omega_{\text{tmp}} := \arccos \left[\frac{n_{(1,1)}}{n_{\text{mag}}} \right] \cdot \frac{180}{\pi} \quad \Omega_{\text{tmp}} = 150.565$$

$$\Omega_{\text{calc}} := \text{if} [n_{(2,1)} < 0, 360 - \Omega_{\text{tmp}}, \Omega_{\text{tmp}}]$$

$$\Omega_{\text{calc}} = 209.435$$

$$u_{\text{tmp}} := \arccos \left(\frac{n \cdot R_{\text{vec}}^T}{n_{\text{mag}} \cdot R_{\text{vecmag}}} \right) \cdot \frac{180}{\pi}$$

 Calculate Greenwich Mean Sidereal Time

$$\text{JD} := 367 \cdot \text{yr} - \text{trunc} \left[\frac{7 \cdot \left(\text{yr} + \text{trunc} \left(\frac{\text{Mo} + 9}{12} \right) \right)}{4} \right] + \text{trunc} \left(\frac{\text{Mo} \cdot 275}{9} \right) + \text{d} + 1721013.5 + \frac{\left(\frac{\text{scnds}}{60} + \text{minits} \right)}{60} + \text{h}_{\text{UTC}}$$

$$\text{Tut} := \frac{(\text{JD} - 2451545)}{36525} \quad \text{Tut} = 0.05870462 \quad \text{JD} = 2453689.18615741$$

$$\text{tmp} := 67310.54841 + (876600 \cdot 3600 + 8640184.812866) \cdot \text{Tut} + 0.093104 \cdot \text{Tut}^2 - 6.2 \cdot 10^{-6} \cdot \text{Tut}^3$$

$$\text{tmp5} := \frac{\text{tmp} - \text{trunc} \left(\frac{\text{tmp}}{86400} \right) \cdot 86400}{240}$$

$$\text{tmp5} = 300.889$$

$$\Theta_{\text{GMST}} := \text{tmp5}$$

$$\Theta_{\text{GMST}} = 300.889$$

 Calculate Target Vector T_{IJK} See Fig. 1

$$\text{lat} = 1.975 \quad \text{long} = -90.082$$

$$\text{target_projection} := R_{\text{earth}} \cdot \cos \left(\text{lat} \cdot \frac{\pi}{180} \right) \quad \text{target_projection} = 2.091 \times 10^7$$

$$T_I := \text{target_projection} \cdot \cos \left[\left(\Theta_{\text{GMST}} + \text{long} \right) \cdot \frac{\pi}{180} \right]$$

$$T_J := \text{target_projection} \cdot \sin \left[\left(\Theta_{\text{GMST}} + \text{long} \right) \cdot \frac{\pi}{180} \right]$$

$$T_K := R_{\text{earth}} \cdot \sin \left(\text{lat} \cdot \frac{\pi}{180} \right)$$

$$\mathbf{T}_{IJK} := \begin{pmatrix} T_I & T_J & T_K \end{pmatrix} \quad \mathbf{T}_{IJK} = \begin{pmatrix} -1.796 \times 10^7 & -1.071 \times 10^7 & 7.212 \times 10^5 \end{pmatrix}$$

$$T_{IJKmag} := \sqrt{(T_I)^2 + (T_J)^2 + (T_K)^2} \quad T_{IJKmag} = 2.093 \times 10^7 \text{ feet}$$

$$u_{calc} := \text{if} \left[\left[R_{vec(1,3)} < 0 \right], 360 - u_{imp}, u_{imp} \right]$$

Calculate Space Station to target vector in IJK coordinates:

$$u_{calc} = 195$$

$$\mathbf{R}_{vec} = \begin{pmatrix} -1.899 \times 10^7 & -1.125 \times 10^7 & 5.892 \times 10^5 \end{pmatrix} \quad \mathbf{V}_{vec} = \begin{pmatrix} 8.448 \times 10^3 & -1.322 \times 10^4 & 1.98 \times 10^4 \end{pmatrix}$$

$$\mathbf{V}_{IJK} := \mathbf{R}_{vec} - \mathbf{T}_{IJK} \quad \mathbf{V}_{IJK} = \begin{pmatrix} -1.028 \times 10^6 & -5.404 \times 10^5 & -1.32 \times 10^5 \end{pmatrix}$$

$$V_{IJKmag} := \sqrt{\left[\left[V_{IJK(1,1)} \right]^2 + \left[V_{IJK(1,2)} \right]^2 + \left[V_{IJK(1,3)} \right]^2 \right]}$$

$$V_{IJKmag} = 1.169 \times 10^6$$

$$\text{latnew} := \left(51.39 \cdot \frac{\pi}{180} \right) - \left[\left(\frac{V_{IJKmag}}{R_{earth}} \right) \cdot 30 \cdot \frac{\pi}{180} \right]$$

$$\text{latnew} \cdot \frac{180}{\pi} = 49.715$$

----- Transformation matrix from IJK to Space Station local orbital Coordinate System.

See Fig. 2.

Assumes $\mathbf{R}_{vec}$ points to center of gravity of Space Station. Same as Space Station local orbital origin.

Euler angle rotation sequence is $Z_A X_A Z_A$.

$$\psi := \text{ascendingnode}$$

$$\Theta := 90 - \text{incl}$$

$$\phi := 90 + \text{argptrues}$$

$$\psi = 209.435$$

$$\Theta = 38.353$$

$$\phi = 91.95$$

$$\text{rot1}_{IJKtoLO} := \begin{pmatrix} \cos\left(\psi \cdot \frac{\pi}{180}\right) & \sin\left(\psi \cdot \frac{\pi}{180}\right) & 0 \\ -\sin\left(\psi \cdot \frac{\pi}{180}\right) & \cos\left(\psi \cdot \frac{\pi}{180}\right) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{rot2}_{IJKtoLO} := \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\left(\Theta \cdot \frac{\pi}{180}\right) & \sin\left(\Theta \cdot \frac{\pi}{180}\right) \\ 0 & -\sin\left(\Theta \cdot \frac{\pi}{180}\right) & \cos\left(\Theta \cdot \frac{\pi}{180}\right) \end{pmatrix}$$

$$\text{rot3}_{IJKtoLO} := \begin{pmatrix} \cos\left(\phi \cdot \frac{\pi}{180}\right) & 0 & -\sin\left(\phi \cdot \frac{\pi}{180}\right) \\ 0 & 1 & 0 \\ \sin\left(\phi \cdot \frac{\pi}{180}\right) & 0 & \cos\left(\phi \cdot \frac{\pi}{180}\right) \end{pmatrix}$$

$$\text{rot1}_{IJKtoLO} \cdot \mathbf{V}_{IJK}^T = \begin{pmatrix} 1.161 \times 10^6 \\ -3.435 \times 10^4 \\ -1.32 \times 10^5 \end{pmatrix} \quad \text{rot2}_{IJKtoLO} \cdot \left(\text{rot1}_{IJKtoLO} \cdot \mathbf{V}_{IJK}^T \right) = \begin{pmatrix} 1.161 \times 10^6 \\ -1.088 \times 10^5 \\ -8.217 \times 10^4 \end{pmatrix}$$

----- Transform target vector in IJK coordinate system to target vector in Space Station local orbital Coordinate System.

$$\mathbf{V}_{LO} := \left[\text{rot3}_{IJKtoLO} \cdot \text{rot2}_{IJKtoLO} \cdot \text{rot1}_{IJKtoLO} \cdot \left(\mathbf{V}_{IJK}^T \right) \right]$$

$$V_{LOmag} := \sqrt{\left[\left[V_{LO(1,1)} \right]^2 + \left[V_{LO(2,1)} \right]^2 + \left[V_{LO(3,1)} \right]^2 \right]} \quad \mathbf{V}_{LO} = \begin{pmatrix} 4.263 \times 10^4 \\ -1.088 \times 10^5 \\ 1.163 \times 10^6 \end{pmatrix}$$

$$V_{LOmag} = 1.169 \times 10^6$$

----- Find $\mathbf{T}_{SHORE}$ vector in SHORE coordinate system.

Determine $\mathbf{V}_{SS}$ vector from Space Station center of mass to SHORE center of rotation.

See Fig. 3.

$\mathbf{V}_{SS}$ is fixed based on Space Station configuration and dimensions and doesn't change.

(verify amount of change due to disturbances and determine if they are significant).

$$\mathbf{V}_{SBtoLAB} := \begin{pmatrix} 0 & 0 & 0 \end{pmatrix} \text{ feet}$$

Note: zero's are place holders until actual dimensions can be obtained.

$$V_{LABtoRACK} := (0 \ 0 \ 0) \text{ feet}$$

From SSP 52000_PHI-WRP. Example of what value will be.

$$V_{RACKtoWORF} := (0 \ 0 \ 0)$$

$$V_{RACKtoWORF} := \begin{bmatrix} -21.7 & (42 + 13.7) & 21.1 \\ 12 & 12 & 12 \end{bmatrix}$$

$$V_{WORFtoSHORE} := (0 \ 0 \ 0) \text{ feet}$$

$$V_{SS} := V_{SBtoLAB} + V_{LABtoRACK} + V_{RACKtoWORF} + V_{WORFtoSHORE} \text{ feet}$$

Translation matrix for Space Station local orbital coordinates to Space Station body fixed Coordinate System.

$$\text{yaw} := 0 \quad \text{roll} := 0 \quad \text{pitch} := 0$$

$$\psi := \text{yaw} \cdot \frac{\pi}{180} \quad \phi := \text{roll} \cdot \frac{\pi}{180} \quad \theta := \text{pitch} \cdot \frac{\pi}{180}$$

$$\text{rot1}_{LOtoSB} := \begin{pmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{rot2}_{LOtoSB} := \begin{pmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{pmatrix}$$

$$\text{rot3}_{LOtoSB} := \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{pmatrix}$$

Transformation of T_{SHORE} vector in Space Station local orbital coordinate system to T_{SHORE} vector in Space Station fixed body Coordinate System.

$$V_{SB} := \text{rot3}_{LOtoSB} \cdot \text{rot2}_{LOtoSB} \cdot \text{rot1}_{LOtoSB} \cdot V_{LO} \quad V_{SB} = \begin{pmatrix} 4.263 \times 10^4 \\ -1.088 \times 10^5 \\ 1.163 \times 10^6 \end{pmatrix}$$

Calculate $T_{SHORElo}$ target vector in Space Station local orbital coordinates:

$$T_{SHORElo} := V_{SB} - V_{SS}^T \quad T_{SHORElo} = \begin{pmatrix} 4.263 \times 10^4 \\ -1.088 \times 10^5 \\ 1.163 \times 10^6 \end{pmatrix}$$

Transformation matrix for $T_{SHOREsb}$ vector in Space Station fixed body coordinates to T_{SHORE} vector in SHORE Coordinate System. Only 2 rotation needed. See Fig. 4. Rotation sequence is:

1. Rotation about $Y_{SB} \leftrightarrow X_{SB}$ aligned with X_{SHORE} .
2. Rotate about $X_{sb} \leftrightarrow Y_{sb}$ aligned with Y_{SHORE} .

$$\psi := 90 \cdot \frac{\pi}{180} \quad \theta := 90 \cdot \frac{\pi}{180}$$

$$\text{rot1}_{SBtoSHORE} := \begin{pmatrix} \cos(\psi) & 0 & \sin(\psi) \\ 0 & 1 & 0 \\ \sin(\psi) & 0 & \cos(\psi) \end{pmatrix} \quad \text{rot2}_{SBtoSHORE} := \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{pmatrix}$$

--- Transform T_{SHORE} in Space Station fixed body coordinate system to T_{SHORE} in SHORE Coordinate System.

ORIGIN = 1

$$T_{SHORE} := \text{rot2}_{SBtoSHORE} \bullet \text{rot1}_{SBtoSHORE} \bullet T_{SHOREIo} \quad T_{SHORE} = \begin{pmatrix} 1.163 \times 10^6 \\ 4.263 \times 10^4 \\ 1.088 \times 10^5 \end{pmatrix}$$

$$\text{rot1}_{SBtoSHORE} \bullet T_{SHOREIo} = \begin{pmatrix} 1.163 \times 10^6 \\ -1.088 \times 10^5 \\ 4.263 \times 10^4 \end{pmatrix}$$

$$\text{rot2}_{SBtoSHORE} \bullet (\text{rot1}_{SBtoSHORE} \bullet T_{SHOREIo}) = \begin{pmatrix} 1.163 \times 10^6 \\ 4.263 \times 10^4 \\ 1.088 \times 10^5 \end{pmatrix}$$

$$SHORE_{el} := \left(\text{atan} \left(\frac{T_{SHORE_{3,1}}}{T_{SHORE_{1,1}}} \right) \right) \bullet \frac{180}{\pi} \quad \text{Elevation Angle: } SHORE_{el} = 5.347 \text{ Deg}$$

$$SHORE_{az} := \left(\text{atan} \left(\frac{T_{SHORE_{2,1}}}{T_{SHORE_{1,1}}} \right) \right) \bullet \frac{180}{\pi} \quad \text{Azimuth Angle: } SHORE_{az} = 2.1 \text{ Deg}$$

Fig. 1

Space Station orbital coordinate system is a
 Local horizontal/local vertical axis coordinate system.
 X_{LO} is in orbital plane in direction of velocity.
 Z_{LO} is parallel to and opposite to R_{vec} .
 Y_{LO} completes right hand system.

Fig. 2A

1. Rotate about K to place I (I' is new axis) at the ascending node.

Fig. 2B

2. Rotate about I' to place K' (K'' new axis) in the orbital plane.

Fig. 2C

3. Rotate about J'' to place I'' (is now X_{Lo}) parallel to X_{Lo} and K'' (is now Z_{Lo}) parallel to Z_{Lo} .

Fig. 2D

Fig. 3

Start of Rotations

Fig. 4A

Rotate about Y_{SB} . Align X_{SB} with X_{SHORE} .

Fig. 4B

Rotate about X_{SB} . Align Y_{SB} with Y_{SHORE} and Z_{SB} with Z_{SHORE} .

Fig. 4C

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