TUTORIAL

Extraction of Geospatial Information from High Spatial Resolution Optical Satellite Sensors

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2. Image quality, radiometric analysis, preprocessing
3. Geometric sensor models and sensor orientation
4. Automated DSM generation
5. Orthoimage generation
6. Automated and semi-automated object extraction (mainly roads and buildings)
7. Land use and land cover mapping
8. Use of HR for mapping, landscape change detection and map update, and comparison to alternative information sources
9. Cartosat mission characteristics, data processing and products
10. Conclusions and outlook

Section 3

Geometric sensor models and bundle block adjustment

T.P. Srinivasan

Overview

- Characteristics of sensor models for Remote Sensing data processing
- Rigorous Sensor Model (RSM) or Physical Model
- Rational Polynomial Model (RPM or RFM)
- Experiments with High-Resolution IRS satellites

Characteristics of sensor models for Remote Sensing data processing

- Sensor model is used to generate reference between acquired image and ground
- They may be classified as generic models, rigorous photogrammetric models and hybrid models
- Rigorous models provide the best accuracies without use of ground control and to provide map accuracies with minimum number of GCPs

Satellite Photogrammetry

- **Similar to Aerial Photogrammetry with additional constraints posed by orbit and active control used for satellite orientation.**

- **A need to model the imaging process precisely to generate Data Products.**

- **The Photogrammetric Adjustment is the process of statistically adjusting all input data viz. image data, ground truth, calibration data and ephemeredes.**

- **Image to Ground relationship is complex and can be established for whiskbroom scanning, pushbroom scanning, linear array (single or multiple), area array CCDs & TDI devices**

Orientation of linescanner Imagery

The determination of orientation in case of a line scanner Spaceborne camera is complicated by following factors among others:

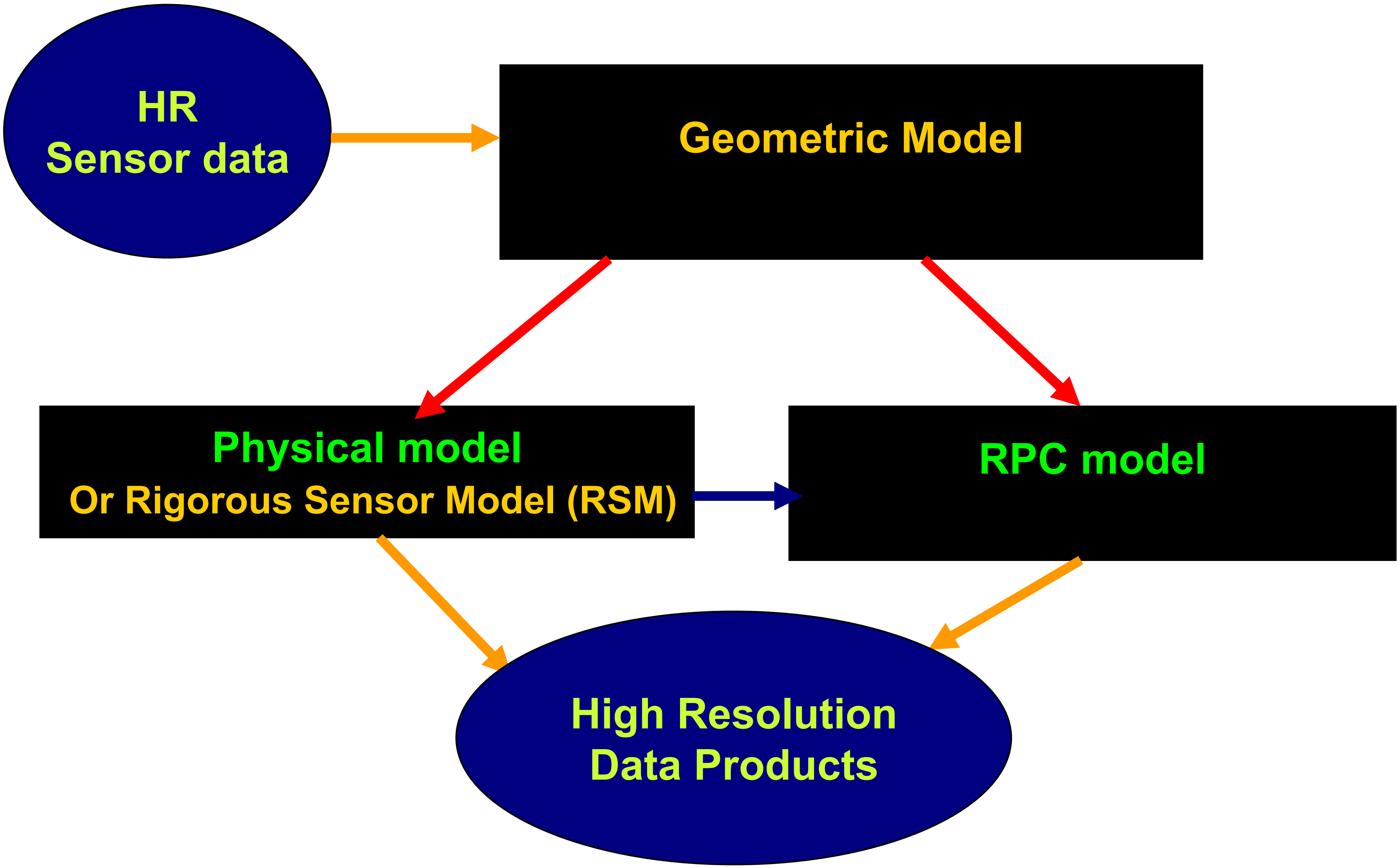
- Earth curvature - results in nonlinear relation between object space and image space.
- Scanning mode - is perspective only in crosstrack direction - in alongtrack direction the imaging is in a parallel projection.
- Each line of the image is acquired from a different camera position.
- Concept of attitude is different in remote sensing satellites as compared to aerial imagery.
- Attitude varies during imaging of a single image

Sensor Models

- DLT model (Direct Linear Transformation Model)
- Parallel Perspective Model (PP)
- The AFFINE Model
- Rational Function Model
- Physical Sensor Model

Non-parametric

Imaging Sensor Model



Physical Model

- Relation between Image & ground
- Earth-sensor-satellite geometry
  - Earth model
  - Payload & Spacecraft model
  - Orbit model
  - Attitude model

Physical Model

Physical models accounts for various distortions relative to the global geometry of viewing i.e

- The distortions caused by the platform (position, velocity, orientation)
- The distortions relative to the sensor (orientation angles, IFOV, detection signal integration time)
- The distortions relative to the earth (geoid-ellipsoid, including relief), and
- The deformations relative to the cartographic projection (ellipsoid-cartographic plane)

The models reflect the physical reality of complete viewing geometry and correct all distortions generated during the image formation

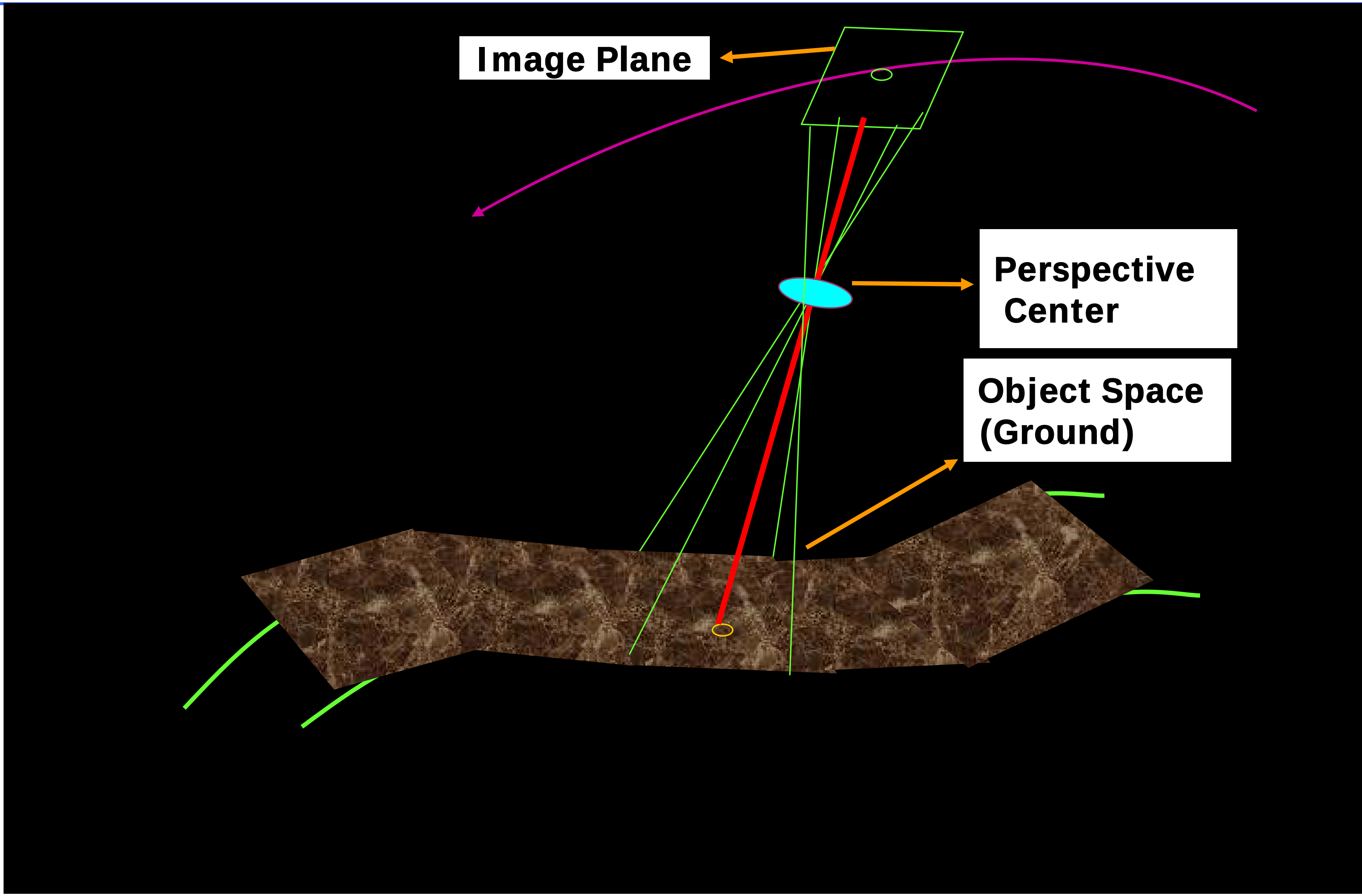
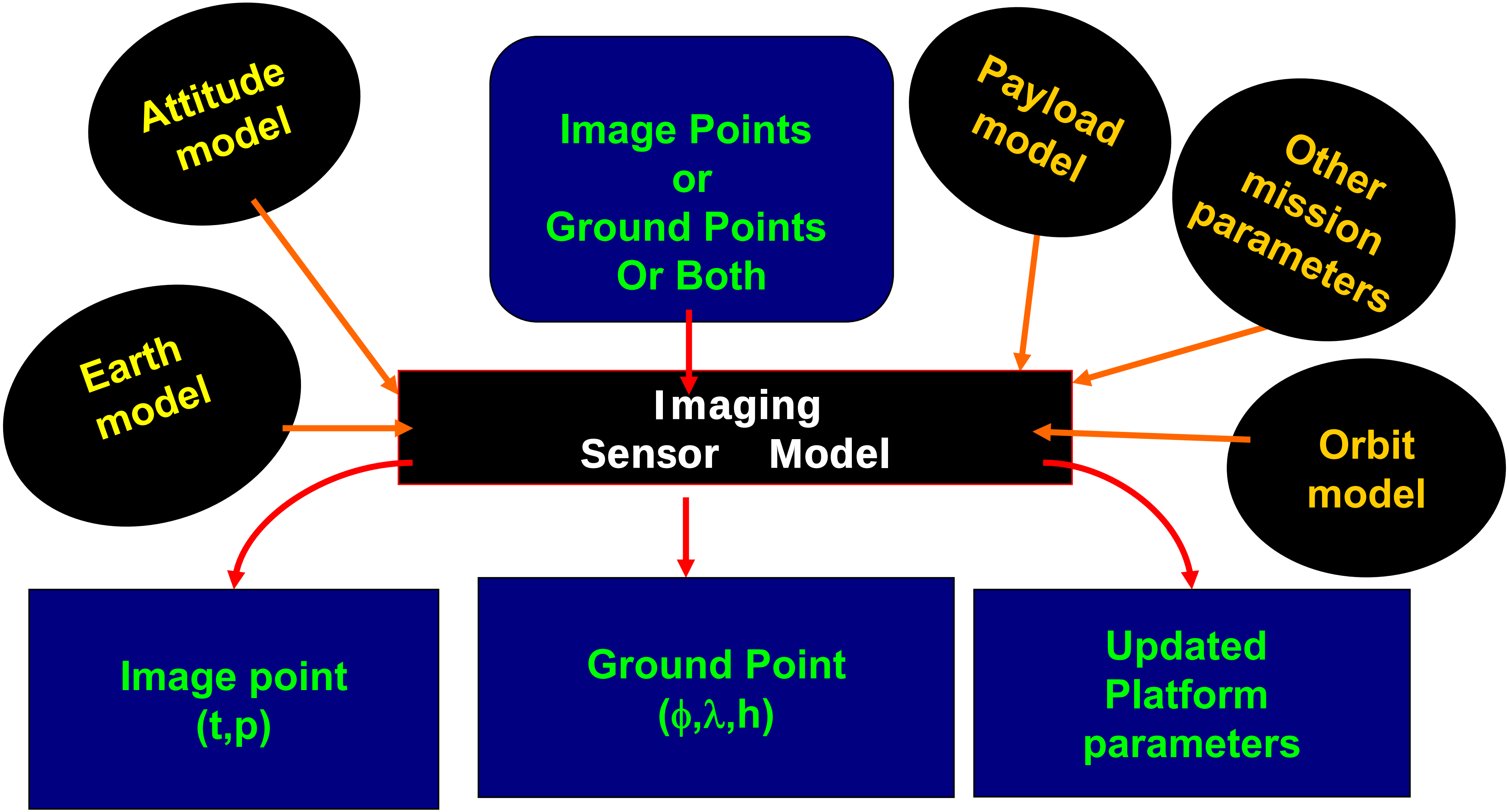


Image Plane
Perspective Center
Object Space (Ground)

Overview of Physical Model



Photogrammetric approach

- Collinearity condition (Image point, object point & perspective center should all lie in a straight line)

  - Image to ground

  - Ground to Image

  - Image to Image

  - Space Resection / Space Intersection

  - Bundle adjustment

Coordinate Systems Used

- Image coordinate System
- Image plane coordinate System
- Sensor coordinate systems (P/L to Optical Axis)
- Spacecraft Body coordinate system (s/c body to sensor)
- Orbit coordinate system
- Earth Centered Inertial (ECI - TOD) system
- Earth Centered Earth Fixed system (ECEF - WGS84) and then to EVE

Payload & S/C model

- **Precise usage of Payload parameters**
- **Alignment parameters**
  - **Focal Length**
  - **Detector size**
  - **Direction of principal axis**
  - **Placement of CCDs with respect to principal axis**
    (Given by angular separation of a number of pixels for each CCD)
- **Spacecraft (Spacecraft alignment angles, Precise Time (SPS, Ground Received Time-GRT, Integration Time, line count etc.)**

Earth model

- Choice of Ellipsoid (WGS-84) & Use of precise parameters

  $$XA^2/ a^2 + YA^2/a^2 + ZA^2/ b^2 = 1$$

- Datum transformation

  - required for Everest, also applicable wherever necessary

- Vertical Datum (geoid – ellipsoid relation)

Orbit Model

- **Time varying State vector (Position: X,Y,Z & Velocity: XD,YD,XD) or Orbital elements**

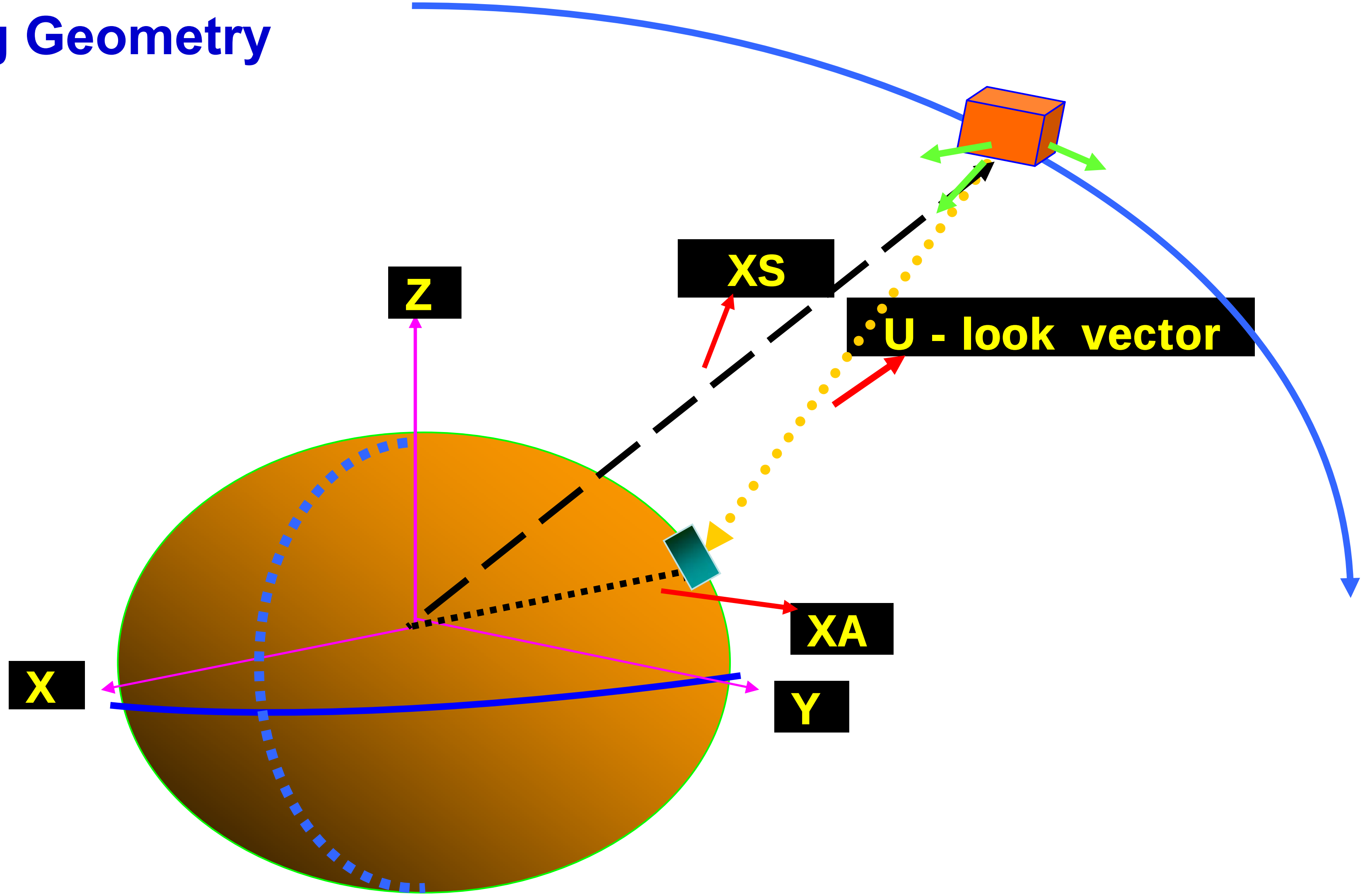
- **Sidereal angle for relating inertial frame to rotating frame**

- **Modelling orbital parameters, if required (Six orbital elements are a, e , i , ω, Ω, T)**

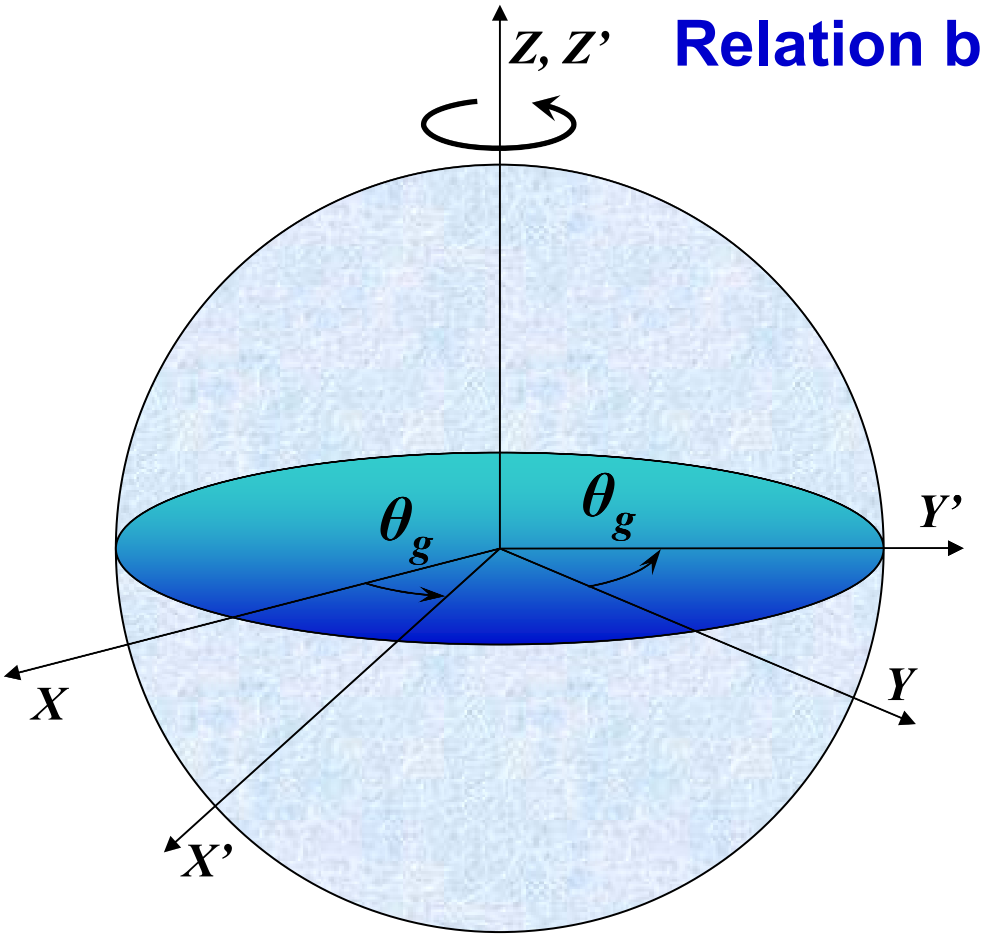
Attitude Model

- Time varying quaternions or Attitudes and gyro rates
- Smoothening of Q's, if required (using local as well as global fitting)
- Rotation sequence & conventions
  - Pitch, roll, Yaw sequence (3,2,1)
- Linear & higher degree error model

Imaging Geometry



Relation between Inertial & Rotating Frames



X, Y, Z = Inertial Frame

X', Y', Z' = Geocentric Frame

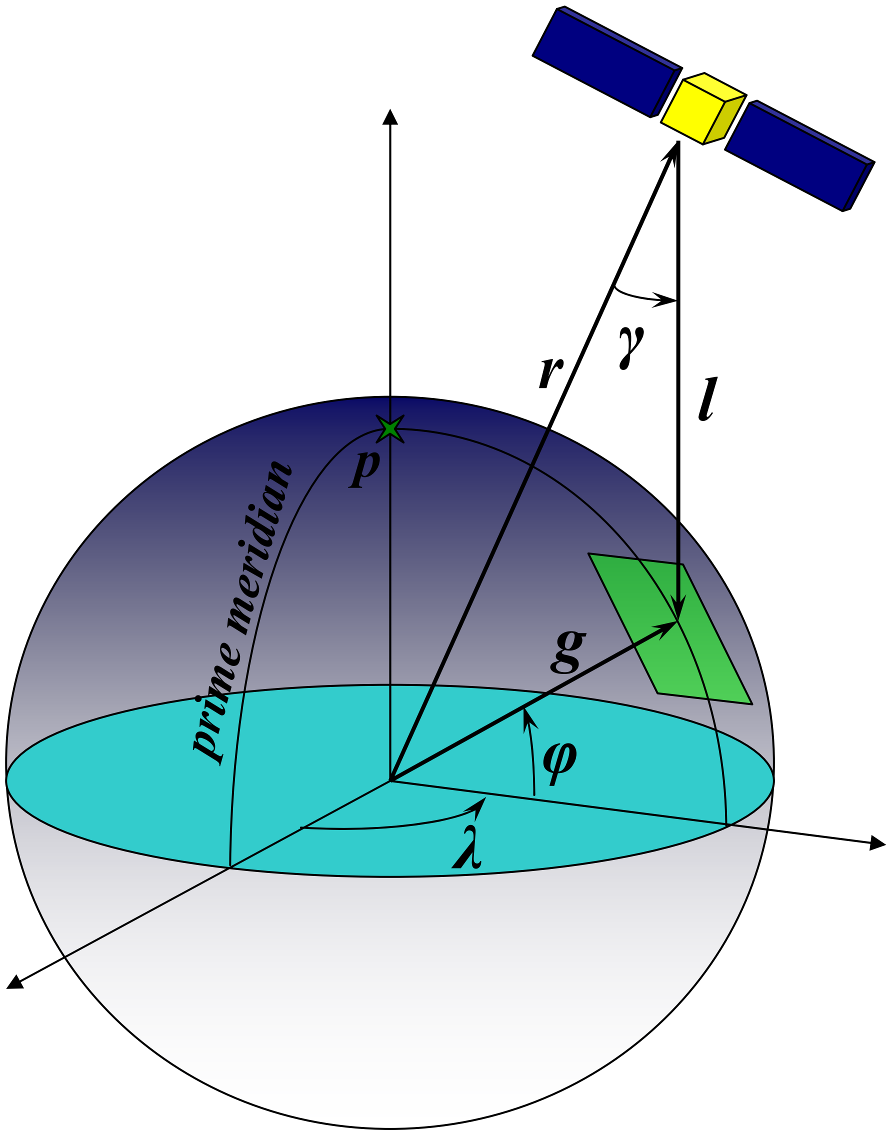
θ_g = Sidereal Angle at time t

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \cos(\theta_g) & \sin(\theta_g) & 0 \\ -\sin(\theta_g) & \cos(\theta_g) & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$A = \begin{bmatrix} \cos(\theta_g) & \sin(\theta_g) & 0 \\ -\sin(\theta_g) & \cos(\theta_g) & 0 \\ 0 & 0 & 1 \end{bmatrix} = \text{TransformationMatrix}$$

$$\vec{V}_R = A.\vec{V}_I$$

$$\vec{V}_I = A^T \cdot \vec{V}_R$$



$$\vec{g}_E = \begin{pmatrix} R_\varphi.\cos(\varphi).\cos(\lambda) \\ R_\varphi.\cos(\varphi).\sin(\lambda) \\ R_\varphi.\sin(\varphi) \end{pmatrix}$$

$$\vec{g}_I = \begin{bmatrix} \cos(\theta_g) & \sin(\theta_g) & 0 \\ -\sin(\theta_g) & \cos(\theta_g) & 0 \\ 0 & 0 & 1 \end{bmatrix}^T \cdot \vec{g}_E$$

$$\vec{l} = \vec{g}_I - \vec{r}$$

Collinearity Equations

$$X_A = X_s + s\,U \quad \text{or}$$

$$(x, y, z)^T = S\,M\,(X_A - X_S)$$

where M is rotation matrix from ground to image

$M = R_{PO} R_{MP} R_A R_o$

X_S is perspective center position

XA ground point

(x,y,z) Image point

- Crux of the 'geometric distortion model' to re-establish the look-vector or correct Viewing direction

Space Resection

- Space Resection based on collinearity condition
- Updation of orientation parameters

Space Intersection

- Two orbits one camera solution
- Single orbit two camera solution

Space Resection

It is the process in which the spatial position and orientation of an image is determined based on image coordinates of the GCPs appearing on the image

- Linearization of collinearity equations with respect to attitude parameters
- Refinement of the parameters iteratively till the stable solution is reached
- Solution converges within 3 or 4 iterations

Space Intersection

It is the process of computing the ground coordinates of conjugate points

- **Linearization of Collinearity equations w. r. t ground coordinates**
- **Refined attitude parameters by Space Resection, are used**
- **Refinement of Ground coordinates iteratively**
- **After 3-5 iterations convergence is achieved**

Stereo Strip Triangulation (SST)

- **DEM generation using resection, intersection & bundle adjustment**

- **Different treatment to the same problem**

- **Physical Sensor Model based on collinearity equations for**
  - **Conjugate points,**
  - **Observation equations based on gcps and**
  - **Pseudo observation equations for exterior and interior orientation parameters.**

- **using a simultaneous least square adjustment of all the measurements**

Stereo Strip Triangulation

Inputs

- Stereo Image data
- GCPs for the acquired region
- Corresponding orbit and attitude data

Outputs

- Ground coordinates of the conjugate points or coarse DEM
- Triangulated Control Points (secondary control points) - TCPs
- Updated satellite orientation parameters
- Geometric Performance parameters of SST

Photogrammetric Model

Relation between object point and corresponding image point is given by

$$\begin{bmatrix} f \\ -x \\ -y \end{bmatrix} = K.M.\begin{bmatrix} X_A - X_S \\ Y_A - Y_S \\ Z_A - Z_S \end{bmatrix}$$

The collinearity equations are given by

$$E_1 = [(-x)M1 + fM2] * \left[\bar{X}_A - \bar{X}_S\right]$$

$$E_2 = [(-y)M1 + fM3] * \left[\bar{X}_A - \bar{X}_S\right]$$

Bundle Adjustment

- Collinearity equations
- Ground control Equations
- Equations for Exterior Orientation Parameters
- Equations for Interior Orientation Parameters

This gives a matrix equation

$$V + \dot{B}\,\dot{\Delta} + \ddot{B}\,\ddot{\Delta} + \dddot{B}\,\dddot{\Delta} = \varepsilon$$

$$\bar{V} + \bar{B}\,\Delta = \bar{C}$$

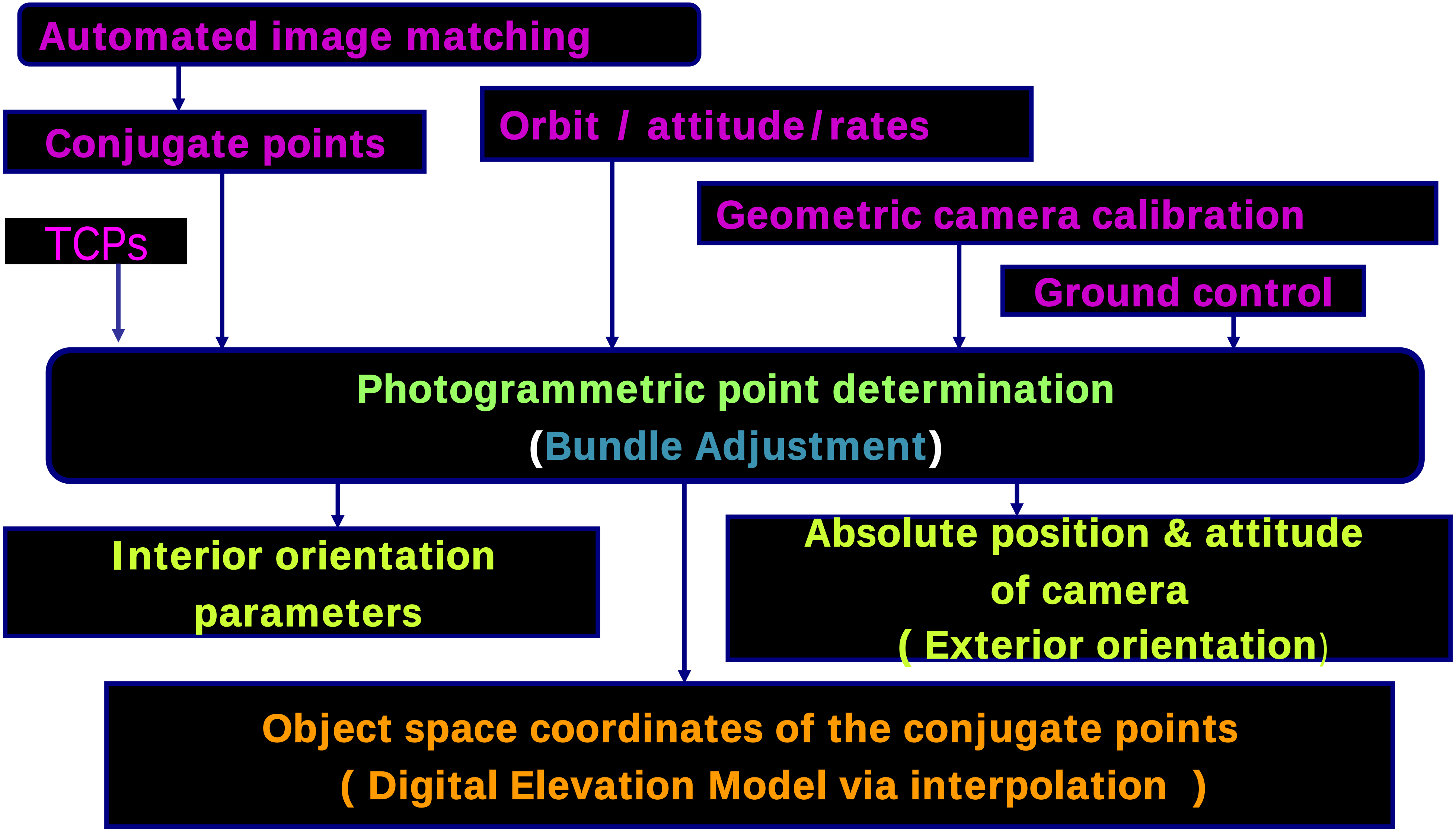
Combined Mathematical Model

Observation equations for collinearity equations, interior orientation parameters, exterior orientation parameters and ground coordinates can be put together as

$$\begin{bmatrix} V \\ \dot{V} \\ \ddot{V} \\ \dddot{V} \end{bmatrix} + \begin{bmatrix} \dot{B} & \ddot{B} & \dddot{B} \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} * \begin{bmatrix} \dot{\Delta} \\ \ddot{\Delta} \\ \dddot{\Delta} \end{bmatrix} = \begin{bmatrix} \varepsilon \\ \dot{C} \\ \ddot{C} \\ \dddot{C} \end{bmatrix}$$

Solving the above set of equations by least-square gives the desired result

Photogrammetric Bundle Adjustment



Rational Polynomial Coefficients (RPC)

- Non-parametric approach
- Alternative Sensor Model or Replacement Model, called Rational Function Model (RFM)
- Narrow field of view of HR imaging system & lack of information on sensor calibration details & other orbit/attitude data
- Polynomial of 3rd Deg
- Hiding orbit/attitude details
- Being used by IKONOS, QuickBird, Cartosat-1 satellites
- Orthokit products

Rational Polynomial Coefficients (RPC)

- Coefficients of ratio of polynomials providing relation between image and ground

- Generally 3rd degree, 80 coefficients

- Image co-ordinate as a ratio of two polynomial functions in the ground co-ordinate:

$$x_n = \frac{p_1(Xn, Yn, Zn)}{p_3(Xn, Yn, Zn)}$$

$$y_n = \frac{p_2(Xn, Yn, Zn)}{p_4(Xn, Yn, Zn)}$$

Orthokit

- Height information taken from GTOPO30
- 90 parameters in a RPC file with meta data
- Orthokit as the end product (as radiometrically corrected or Geo corrected with RPC file)
- Accuracy comparable with Physical Sensor Model
- Terrain-independent approach is convenient to use
- Compatible with COTS s/w packages

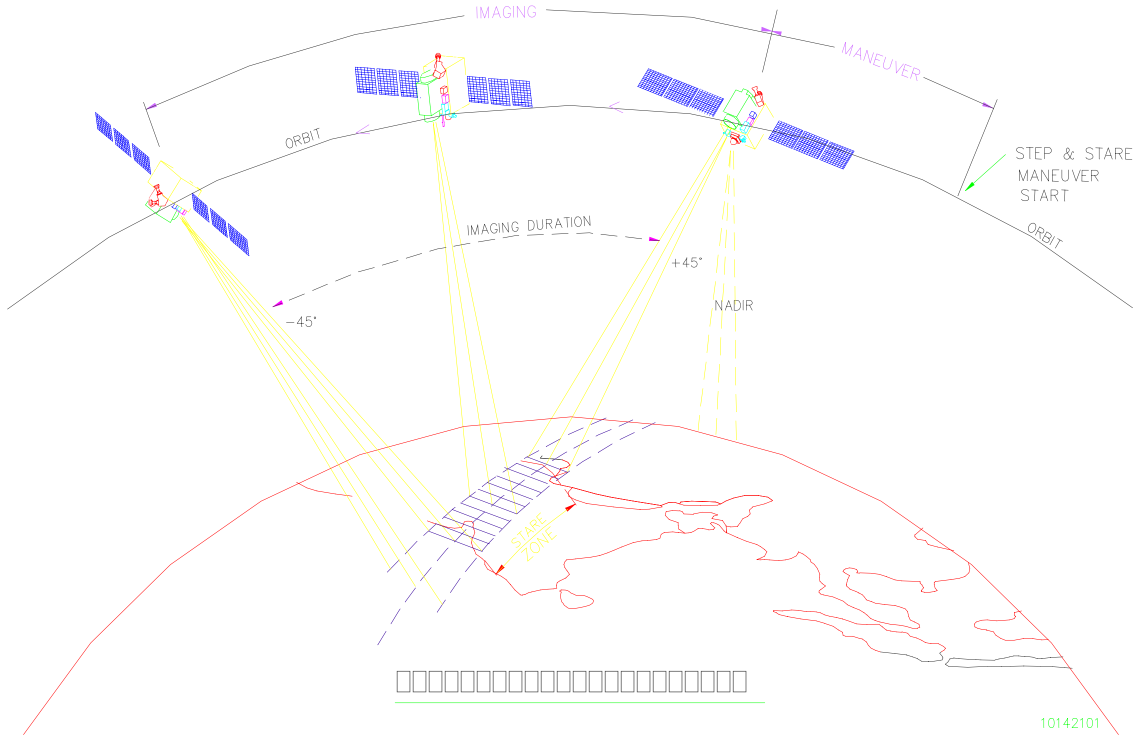
RPC Generation Methodology

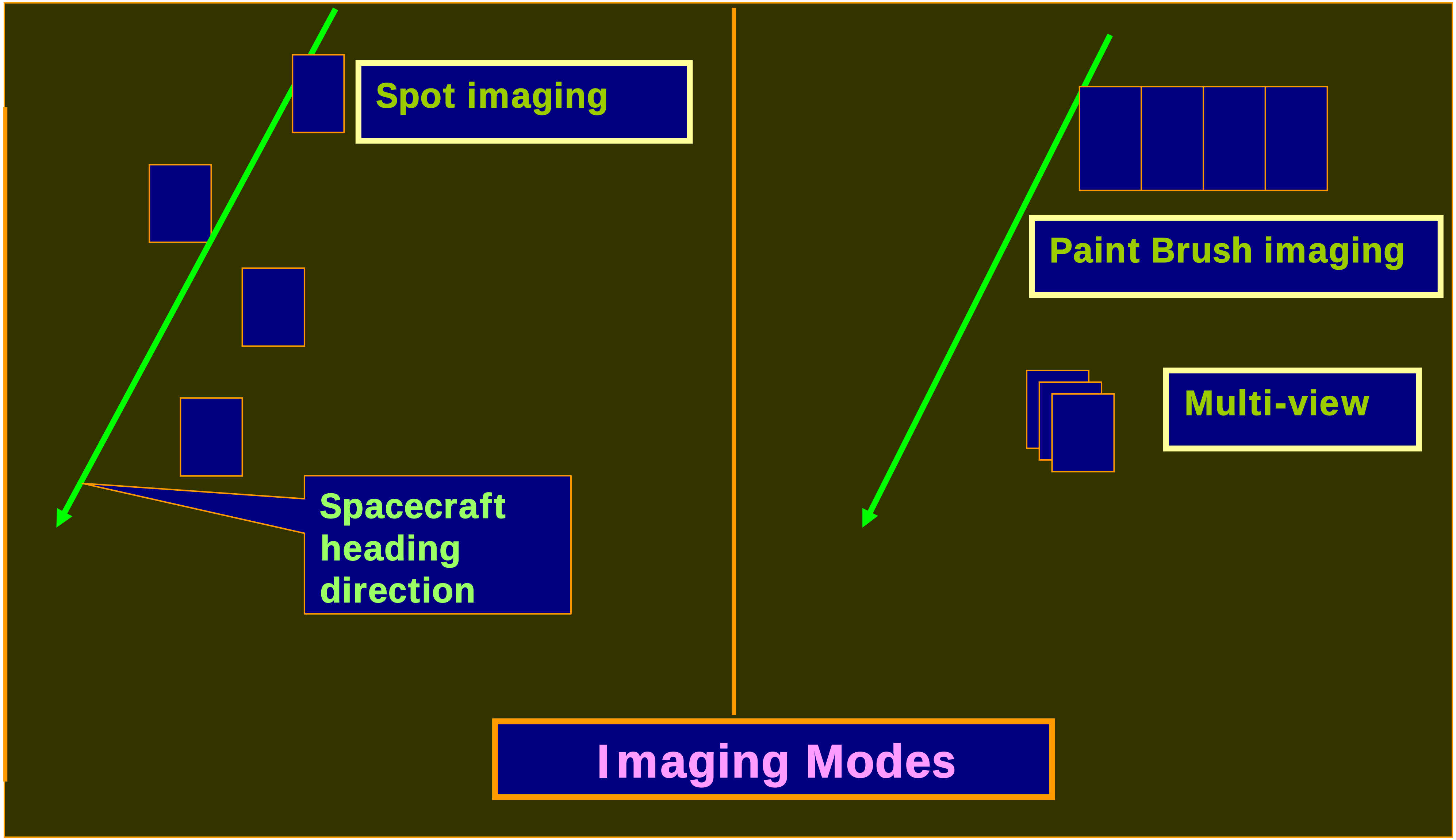
- Computation of ground coordinates for every scan line and pixel number using the rigorous image to ground model.
- Based on the input grid interval, computation of ground coordinates at regular interval.
- Extracting the Minimum and Maximum heights for the particular area from the Global GTOPO DEM
- Based on Minimum and Maximum heights, formation of various constant elevation layers.
- Generation of multiple grids corresponding to each height using ground to image transformation thro' rigorous physical model.
- Estimation of RPCs using the grid of object points and the corresponding image points by least square technique.

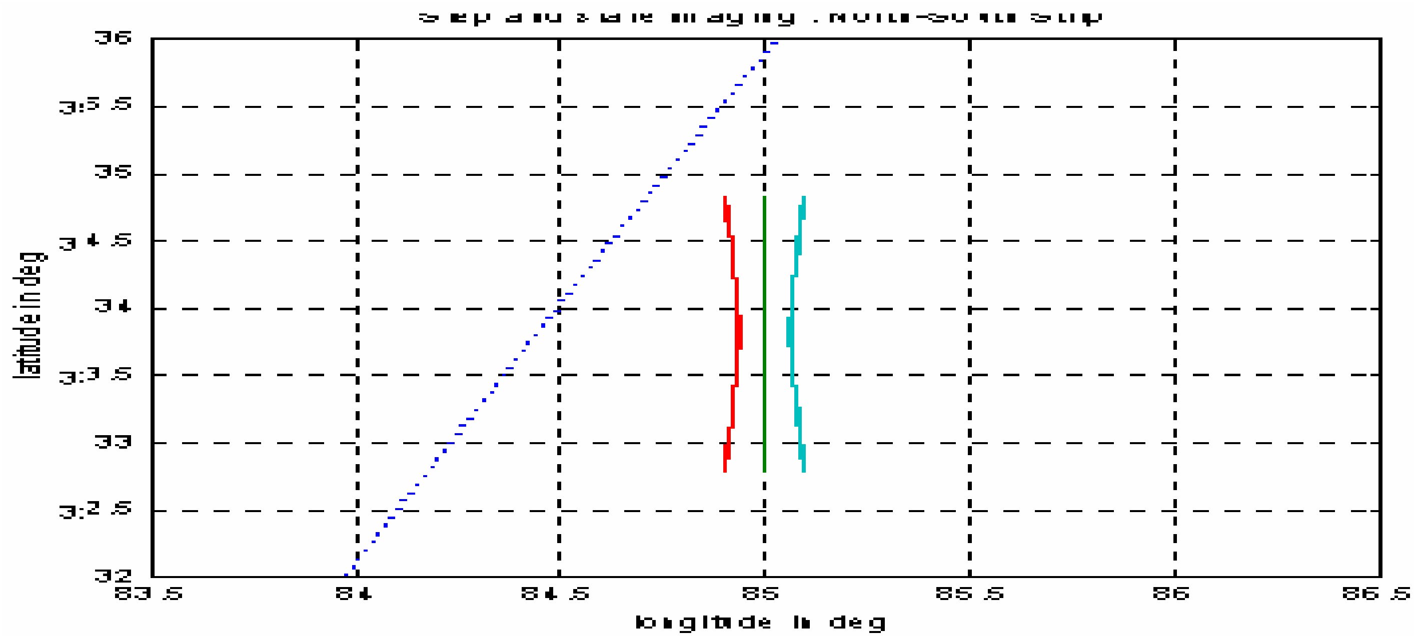
Sensor model for Step and Stare imaging

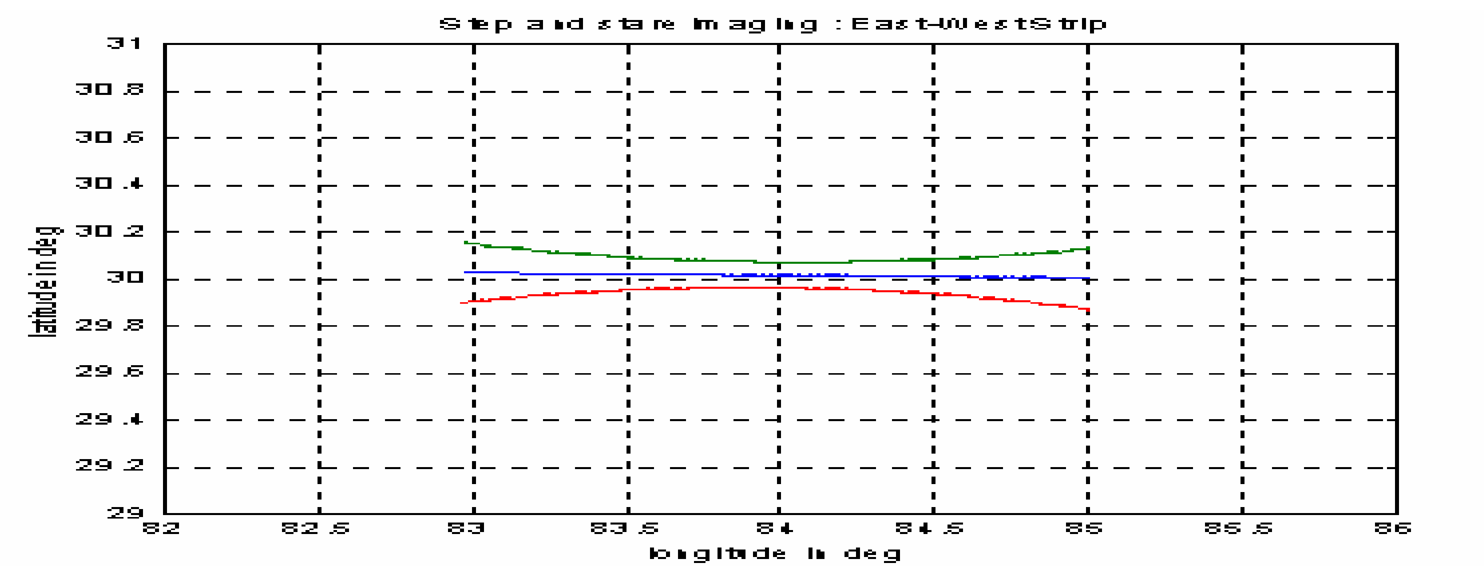
- **STARING : To make the spacecraft camera move slower than the nominal ground track velocity of the spacecraft .**
- **STEPPING: To impart the initial bias to make the camera to look ahead of sub-satellite point**
- **Pitch and Roll Control**
  - **To maintain uniform GSD throughout imaging.**
  - **To compensate for earth rotation.**
- **Yaw Control**
  - **To maintain CCD scan line at the desired angle wrt CCD trace.**

Step and Stare imaging




Spot imaging
Paint Brush imaging
Multi-view
Spacecraft heading direction
Imaging Modes


latitude in deg
longitude in deg
36
35
34
33
32
83.5
84
84.5
85
85.5
86
86.5


Step and stare imaging : East-West Strip
latitude in deg
longitude in deg
31
30.8
30.6
30.4
30.2
30
29.8
29.6
29.4
29.2
29
82
82.5
83
83.5
84
84.5
85
85.5
86

Geometric Performance Evaluation

- Estimation of ground coordinates using GCPs and refined orientation parameters
- Estimation of image position using GCPs and refined orientation parameters
- Computation of statistics
  - ⇨ Difference between actual and estimated ground coordinates to get residuals
  - ⇨ Difference between actual and estimated image positions to get residuals
  - ⇨ Root Mean-Square (RMS) of residuals
  - ⇨ Standard Deviation of residuals
- Data Quality Evaluation of products (system , precision & ortho)

Sensor model for HR IRS satellites

- ‘Imaging model’ being used for nadir viewing, off-nadir, Step-Stare imaging mode
- Adopted for earlier ISRO missions viz. IRS-1C/1D & IRS-P6
- Tested for HR Imaging Along The Desired Direction Using Linear CCD Array
- Being used at present in Data products s/w and Stereo Strip Triangulation s/w for Cartosat-1 & will be adopted for Cartosat-2 also.
- Model accuracy depends on input knowledge of various parameters (uncertainties in orbit, attitude, camera parameters & other alignment angles, GCPs & DEM)

Merits and benefits of using Sensor Model for HR IRS satellites

- Precision correction/ Geometrical correction with GCPs
- Standard correction/ Geometrical correction without GCP (though limited by system knowledge)
- Ortho correction using GCPs & DEM
- DEM generation
- In-flight calibration exercises
- Stagger estimation
- Ovelap analysis
- Orthokit products

Conclusions

- Both Physical model & RPC model are useful tool for exploiting high resolution satellite images for Mapping applications
  viz. Ortho-rectification, 3-D feature collection, DSM generation, multi-sensor integration etc.

- Scope exists for further Research & Development work on both Physical model & RPC based approach towards current & future HR earth and space missions

Thank You all