COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

SPOT IMAGING INSTRUMENT (HRV) MODELLING FOR INTERACTION WITH THE ATTITUDE DETERMINATION AND CONTROL SYSTEM OF THE IMAGING SATELLITE

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Abstract. *The growing need for a better quality in satellite images, in terms of image resolution, is also translated as requirements of a still better accuracy in the satellite control and attitude determination. Due to this, the search for solutions that could supply these needs is still far from its end. This work main concern is the SPOT satellite imaging instrument modelling and the establishment of a vectorial field relating each imaged point to the satellite mass center. From the study of such a field one is able to extract important information on the satellite attitude. Also in this work we show some simulation results, concerning attitude determination, related to the interaction between imaging and the attitude determination and control system of the satellite.*

Keywords. *Satellite, attitude, determination, modelling, imaging.*

1. INTRODUCTION

Remote sensing (RS) satellites provide earth observation products for agriculture, cartography, environment, urban planning, surveillance, forestry, land use/land cover mapping, natural hazards (flood, risk management), water management, natural resources, oil and gas exploration, etc. Spot Image is the world's leading supplier of geographic information from optical and radar earth observation satellites. Each SPOT satellite carries two HRV (High Resolution Visible) imaging instruments. This work main concern is the SPOT-2 satellite imaging instrument operation modelling and the establishment of a vectorial relationship between each imaged point and the satellite center. Once established such relationship, from the study of its characteristics together with some imaging data, one could extract important information on the satellite attitude. Also in this work we comment some possible actions that could lead to an effective interaction between imaging and the attitude determination and control system of the remote sensing satellite.

2. COORDINATE SYSTEMS

XYZ – Inertial geocentric coordinates system (CGI). It is a right handed system having celestial equator as fundamental plane and X axis pointing to the vernal equinox (ϒ).

rpy – Orbital system (roll, pitch, yaw). Fixed to the orbit, right handed, centered in the satellite mass center, y axis (yaw) points to the Earth center.

xyz - Body system of coordinates. Right handed, fixed to the satellite mass center, coincident with the rpy system in case of null attitude deviations.

3. SPOT IMAGING MODELLING.

SPOT satellites have been chosen for the purposes of this work due to the simplicity of its operation, the quality of photosensitive CCD imagery (photographic resolution) as well as the vast amount of documentation concerning the operation itself and images to easily check results. Geographic location of pointing directions is the main purpose of the imaging modelling we conduct here. Given a time instant, t, row and column (image) elements, (I,J), of a certain imaged pixel, supposed known are the vehicle position and preliminary attitude, one can get the imaged pixel geographic coordinates (latitude, longitude). To accomplish such a task it is necessary to relate each imaged pixel to an unique pointing direction.

3.1 - SPOT Satellites: Modelling data.

- Circulate Earth (14+5/26) times a day at an altitude of 830 km (nominal).
- Average orbit period in a 26 days cycle: t = 101.4 min.
- Sun synchronous orbit: It always passes above the same area at the same local time.
- Inclination: 98.7°.
- Imaging instrument: HRV, "High Resolution Visible".
- HRV operation modes: Vertical, Vertical "Twin" and Oblique.
- Vertical and oblique viewing with use of a Strip Selection Mirror, SSM: 91 different positions or steps (from 3 to 93). Each step = 0.6° => 8.7 km (vertical viewing), 11.5 km (extreme oblique viewing).
- Look angles: ψ_x e ψ_y. Responsible for the deviation of the HRV imaging axis. In the case of HRV-1 (used in this simulation), $\psi_x = 0.53°$, is equivalent to a slight ahead deviation (considering subsatellite point) of imaging line. ψ_y in this work is called ϕ.
- CCD detector: Linear 6000 element array.
- Vertical viewing: 60 km simultaneously imaged.
- Pointing precision (attitude): 0.15°.
- AOCS (Attitude, Orbit and Control System) fine pointing mode: Rate integrating gyroscopes, horizon and sun sensors.
- Autonomous control: Sensors output connected to on board computer (which starts actuators - reaction wheels and magnetic coils).
- Ground Patch Area: Point on the ground related to one image pixel.
- Panchromatic mode (P): Black and with, fine geometric details.
  Columns distance $\cong$ 10m
  Time between imaging lines: $\cong$ 1.504 ms
  Raw scene: 6000 X 6000 pixels
  Central pixel (C_0) = (3000,3001)
  Corners: C_1=(1,1); C_2=(1,6000); C_3=(6000,1); C_4=(6000,6000)
- "Push-Broom": Operational principle.
- β: Viewing angle ($-7.5° \le \beta \le 7.5°$ => vertical viewing;

7.5° ≥ β ≥ 7.5° => oblique viewing).

3.2 – Identification of imaging pointing direction.

We look the direction of vector $\bar{a}$ which points to the center of the (I,J) imaged pixel. At first we consider "V" vertical viewing (that means β=0°) and panchromatic mode. We call $\vec{o}$ the optical axis, with origin in the sat mass center, pointing to the center of line I, which contains the (I,J) imaged pixel. In the case of β=0° and null attitude error (Fig. 1), $\vec{o}$ coincides with $\vec{z}$ (body system), which, in turn, coincides with $\vec{y}$ (yaw axis- orbital system).

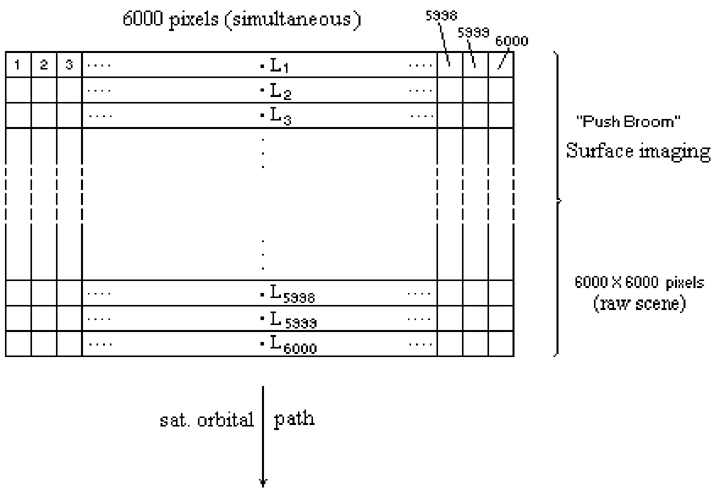

Fig. 1 – Raw scene. Surface imaging model: β = 0°.

Suppose that in the nominal situation the subsatellite point, P_i, coincides with the center of the imaging line, L_i , at instant t_i. The optical axis, $\vec{o}$, fixed to the camera, points to the center of the complete imaging line (6000 pixels), that means, exactly between pixels 3000 and 3001 (Fig. 2). The successive lines are imaged as a result of satellite orbital movement.

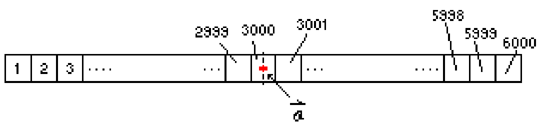

Fig. 2 – Optical axis between pixels 3000 and 3001.

3.3 - HRV imaging: Panchromatic mode.

This imaging mode makes it possible to visualise geometric details with 10m resolution. Each line imaging time, Δt ≅ 1.504 milliseconds, is a function of in orbit satellite velocity. A simulation of one such scan can be accomplished as follows: Given t_1, image acquisition starting time, one has L_1, line 1 central position, then

Position 1 (t_1): Imaging of line 1 (6000 pixels = 60 km).

We add Δt = 1.504 ms and propagate satellite state (position/velocity) with use of ephemerides data (supplied together with SPOT images) and an interpolating (8^{th} order) polynomial. As a result we reach position 2 coincident with the center of line 2, L_2, which, in nominal conditions, stands 10m away from the previous line center.

Position 2 (t_2): Imaging of line 2.
We add Δt and propagate satellite state. As a result we reach the next line center.

Position 3 (t_3): Imaging of line 3.
We add Δt and propagate satellite state. As a result we reach the next line center.

Thus, repeating the described procedure until line number 6000, it is possible to simulate the attainment of a complete 6000 X 6000 image.

Obs.: $t_{i+1} = t_i + \Delta t$. Given t_1, the i element of pixel (i,j) identifies the instant t_i of line acquisition, i. e., pixel (I,J) is imaged together with the entire i^{th} line at the instant t_i, where

$$t_i = t_1 + (i-1)\Delta t. \tag{1}$$

from t_i, with the help of an interpolating polynomial to the orbit data, one can calculate satellite position at that moment in geodetic reference system. The conversion from that system to geocentric inertial is easily accomplished (de Brum, 1994) and results vehicle position P(u,v,w).

3.4 – Calculation of the intersection point , P_{int} , between earth ellipsoid and optical axis.

Positioned above an ellipsoidal earth, the vehicle has its subsatellite point given by the intersection between reference ellipsoid and earth center direction, from the satellite mass center. Such subpoint also identifies the imaging line center, as discussed before. Well, given an instant *t*, once known the satellite position, one may calculate the optical axis direction, $\vec{o}$, which points to the imaging line center at that instant. Such calculation may be accomplished once obtained the intersection point discussed in the early paragraph. Given (in CGI):

P(u,v,w) = Satellite position,
$\hat{a}_{XYZ} = (a_X,a_Y,a_Z)$ => Unit vector in the optical axis direction, we wish to calculate:
$\vec{a} = s.\, \hat{a}_{XYZ}$ => Vector in the optical axis direction.

The problem is to find out the intersection between vector $\vec{a}$, that extends from the satellite center, and the ellipsoid representing earth surface (Hambrick and Phillips, 1980). Inertial coordinates of vector $\vec{a}$, which points to that particular site imaged by pixel (I,J), are $(s.a_X,s.a_Y,s.a_Z)$ (Fig. 3). Once set the problem, all we have to do is calculate 's'.

Earth surface is given by

$$\frac{(x^2+y^2)}{R_E^{\,2}} + \frac{z^2}{R_P^{\,2}} = 1, \tag{2}$$

where R_E stands for equatorial earth radius and R_P is the polar radius. The coordinates of P_{int} are given by

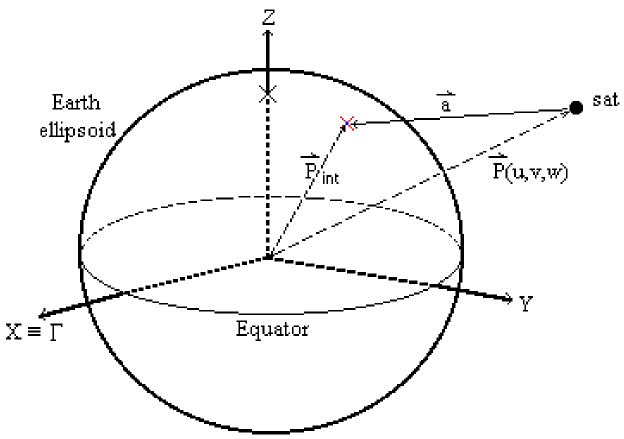

Fig. 3 – Intersection between earth ellipsoid and the line in the direction of $\hat{a}_{XYZ}$.

$$\vec{P}_{int} = \vec{P} + \vec{a} = (u + s.a_X , v + s.a_Y , w + s.a_Z) \quad (3)$$

By substitution of $u+s.a_X$, $v+s.a_Y$, $w+s.a_Z$ by x, y, z in the earth's surface equation, one gets

$$\frac{(u + s.a_X)^2 + (v + s.a_Y)^2}{R_E^{\,2}} + \frac{(w + s.a_Z)^2}{R_P^{\,2}} = 1. \quad (4)$$

When a solution for 's' exists, one may find two values for this parameter, corresponding to two intersection points between the line and the ellipsoid. The one we look for represents the nearest (to the satellite) intersection point. Obtained the intersection point (related to the point (I,J) imaged at the instant t_i), one is ready to get the geographic coordinates (latitude, longitude) of such point.

3.5 – Pointing direction, $\vec{a}$, of each pixel in a row (6000 pixels).

By inclusion of specific deviations, once known the optical axis direction, one can get the pointing directions, $\vec{a}$, of each pixel in a complete 6000 pixels row. Each direction is identified by its column number "J" inside the imaged row. The intersection point identification of each direction with the earth ellipsoid is a task accomplished as discussed in the earlier section.

When $\beta = 0°$, the optical axis points the same direction of z axis (body system). Any non intentional deflection of this axis with respect to the subsatellite point implies existence of attitude errors (Fig. 4).

To the P_i position we associate the imaging of line i. Then,

Nominal situation: xyz and rpy systems => coincident.

Attitude deviations make xyz ≠ rpy; θ_r, θ_p and θ_y, positive rotations about roll, pitch and yaw axes, respectively, express such deviations.

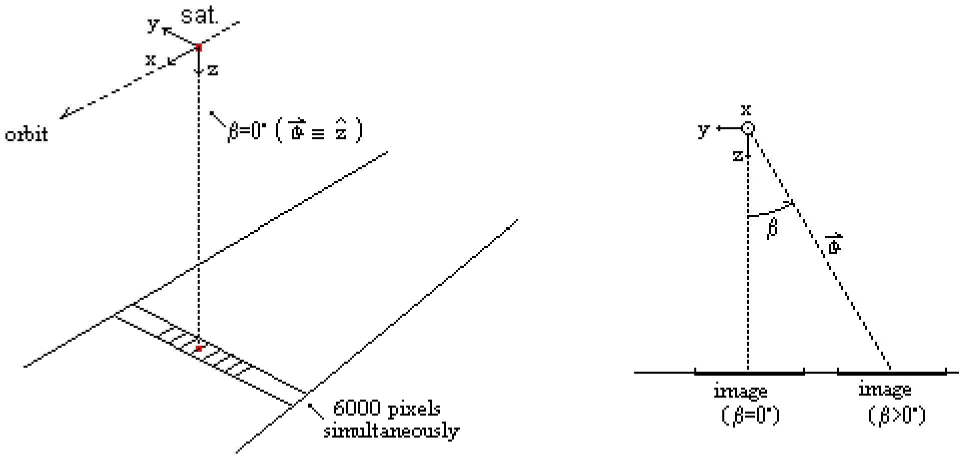

Fig. 4 – Optical axis, $\vec{o}$, identification and relation with β.

3.6 – Attainment of vector $\vec{a}$, which points to the center of pixel (I,J).

$\vec{a} = \vec{a}(x,y,z)$ => body coordinates system

Defining angle ϕ, from the optical vector, $\vec{o}$, in the same direction of the imaging line, pointing to the center of pixel (I,J), according to Fig. 5.

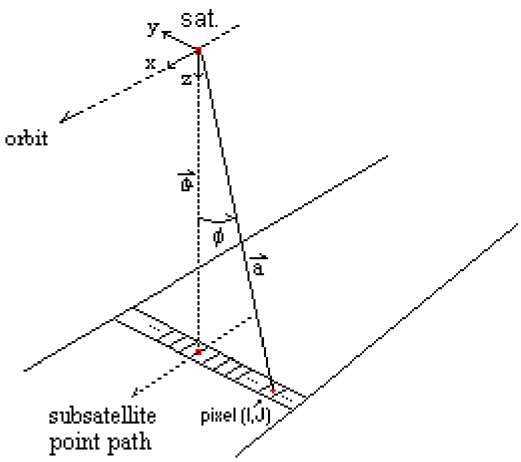

Fig. 5 - ϕ angle definition.

When $\phi = 0°$ => $\vec{o} \equiv \vec{a}$, where $\hat{a} = \vec{a} / |\vec{a}|$. When $\phi \neq 0$, $\phi = \phi(J)$ defined according to Fig. 6. To each pixel (I,J) is associated one direction $\mathbf{\hat{a}}$ which depends on column J in question. The direction of $\mathbf{\hat{a}}$ is a function of ϕ, which in turn is given by

$$\phi(J) = -\phi_{max} + (J - 1)d\phi \, , \quad J=1,2,..., 6000. \tag{5}$$

Where $-\phi_{max} \geq \phi \geq \phi_{max}$

$\phi_{max} = 0.5/13.89$ rad (field of view - FOV)

$d\phi = \phi_{max} / 2999.5$ ($\cong 6.9001031772 \text{ X } 10^{-4}$ °)

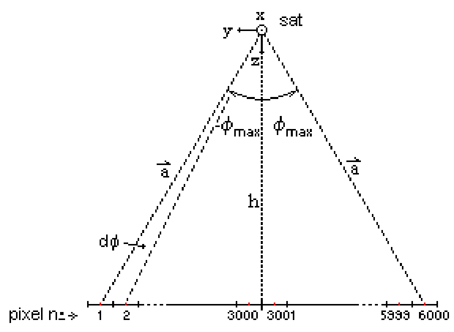

Fig. 6 – Definition: $\phi = \phi(J)$.

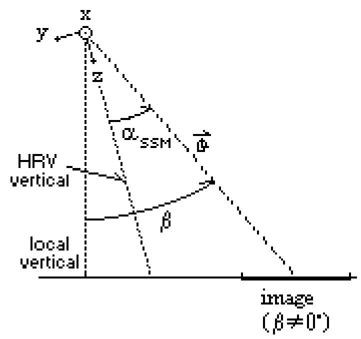

Fig. 7 – Relationship between β and α_{SSM}.
Obs.: ϕ varies in the same plane (ϕ varies around $\vec{o}$).

When $\beta = 0$ ("V Vertical Viewing"), $\vec{o} \equiv \vec{z}$. Viewing angle, β, defines the optical axis direction with respect to local vertical.

When $\beta \neq 0$, $\vec{o}$ dislocates with respect to local vertical. In this case, the deflection of $\vec{o}$ is related with the mirror position angle, α_{SSM}, which integrates the variation expressed by β and takes place in the same plane perpendicular to the satellite velocity vector (Fig. 7). In our case (for the image we used), we had

$$\alpha_{SSM} = -26.24°.$$

Another important angle in obtaining $\vec{a}$ is Ψ_x ("look angle"), which deviates the HRV-1 optical axis (FOV center) a little ahead from the subsatellite point. Thus, the imaging line center is located a little ahead from the subsatellite point. Such angle, in the case of HRV-1, amounts 0.53°.

As ϕ and α_{SSM} vary in the same plane and both refer to the same HRV instrument vertical, we define

$$\phi' = \phi(J) - \alpha_{SSM} \tag{6}$$

Obs.: The negative signal in the previous expression is related to the assumed negative westward variation, contrary to the SPOT definition (SPOT assumes negative signals to eastward variations => $\alpha_{SSM}<0$). For any ϕ' and Ψ_x one has (Fig. 8)

$$\hat{a} = \cos\phi' \,\mathrm{sen}\Psi_x \,\hat{x} - \mathrm{sen}\phi' \cos\Psi_x \,\hat{y} + \cos\phi' \cos\Psi_x \,\hat{z}\,. \tag{7}$$

Once obtained **â**, in body coordinates (xyz), pointing to the imaged at instant t_i pixel (I,J), one has to identify the point on the earth's surface (in terms of latitude and longitude) which refers to that pixel. Such identification involves some coordinate system transformations, as well as a previous vehicle position and attitude knowledge. In the next section we discuss this matter.

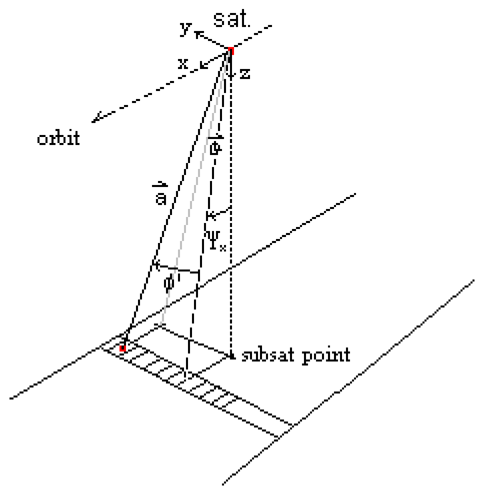

Fig. 8 – Definition of vector â.

3.7 - Transformation: Image coordinates (I,J) to geographic coordinates (latitude, longitude).

Starting from vector â in satellite body coordinates, $\hat{a}_{xyz}$, one may obtain, with previous knowledge of vehicle attitude, the same vector in orbital coordinates, $\hat{a}_{rpy}$. A new transformation results in the same vector in inertial coordinates, $\hat{a}_{XYZ}$. In this last frame (XYZ) we are able to identify the area on earth surface imaged by pixel (I,J). The point in question is given by vector $\vec{P}_{int}$, and is obtained from the intersection point between earth surface and the line in the direction of $\hat{a}_{XYZ}$ (Fig. 3). In the block diagram of Fig. 9 we outline the described transformations.

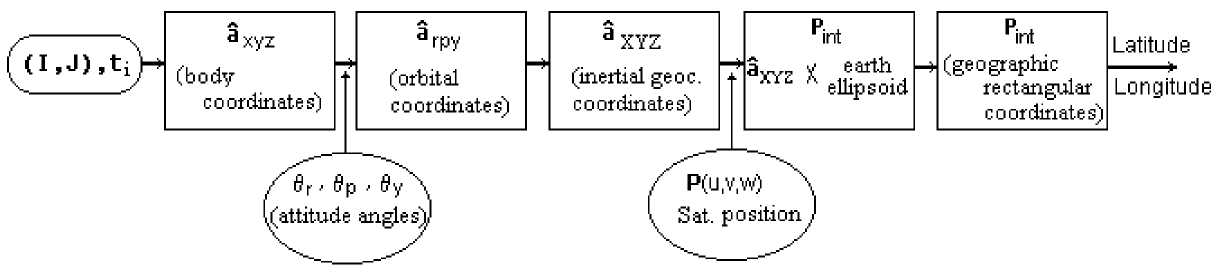

Fig. 9 – Scheme of transformations involved in obtaining the geographic coordinates of pixel (I,J) imaged at instant t_i.

With such transformations in hands, it is possible to assign a vector direction to each pixel in an image. The establishment of such a vector field makes it possible to use the directions on the purpose of attitude sensing. All the work done on that purpose is well described in de Brum (1999). A brief description of some obtained results is performed in the following paragraphs.

3.8 - Program "RS-IMAGING".

The program, in FORTRAN 77, was developed on the purpose of calculating geographic coordinates (latitude, longitude) of some especial (identified) points in an SPOT panchromatic image, starting from its image coordinates (I,J). Input data to the program were the satellite ephemerides and some additional data concerning the image in use (SPOT-2, HRV-1, panchromatic, July, 29th, 1994) obtained by the ATUS/DGI/INPE (SPOT bureau in S. J. dos Campos/SP). For the described input data we calculated satellite position in a few instants (including the initial instant of image acquisition) in geographic rectangular coordinates and transformed it to inertial coordinates. The satellite movement in the meanwhile of one image acquisition ($\cong$ 9 sec) is accomplished by interpolation of ephemerides data, with t_1 = 13:37:28.94937 GMT corresponding to the image starting time (ATUS/DGI/INPE). From this starting position the simultaneous imaging of 6000 columns (one entire panchromatic line) may be done according to what we have described before. Any line imaging may also be simulated with use of time increments and is a function of image coordinate “i”, $t_i = t_1 + (i-1)\Delta t$. In our case, we did not wish one complete image simulation, but, for certain given input data (respective to the used image): (I,J) => Image coordinates; t_1 => image starting time (= t_0), the geographic coordinates, in terms of latitude and longitude, of the point on earth surface imaged by that pixel. The column number, J, identifies the optical axis deviation, $\phi(J)$, related to each one of the 6000 columns simultaneously imaged in one line. Once identified the optical axis pointing direction and the time of such pointing, with knowledge of satellite position and attitude, one may find, through all the transformations described earlier, the geographic coordinates of the imaged pixel. The program "RS-IMAGING” do all these transformations and accomplish such task.

4 - IDENTIFICATION OF ATTITUDE DEVIATIONS.

From one panchromatic SPOT image, it is possible to identify, in it, some particular points with latitude and longitude well known. The useful patterns may represent natural or artificial marks visible in the image. Examples of such marks are forking rivers, crossing avenues, streets, etc. Regarding what happens in stellar sensing, we performed here the attainment of a catalogue containing a sufficient number of points that represent visible and identifiable marks. The calculus of latitude and longitude, as seen from the satellite and its image, of an identified point (subject discussed earlier), associated to the actual geographic coordinates of the same point, may establish a difference between what is calculated and what is known. The existence of such difference suggests the presence of deviations in the known vehicle attitude and may be used in its determination or refinement (de Brum, 1999).

5. SPOT SATELLITE ATTITUDE DETERMINATION WITH USE OF IT’S IMAGING INSTRUMENT: SOME RESULTS.

With use of the relationships mentioned in the former paragraph, we calculated attitude angles related to both, the imaging of the city of São Paulo (Brazil), obtained by SPOT-2 (HRV1) in July 7th ,1994 at 13:37:28.94937 h (GMT), and to the identification of several points in the city. Special software to integrate all involved tasks, i. e., image processing, data handling, attitude calculation, template matching, programs managing, etc., was developed to accomplish such a purpose. The identification of some known points, in terms of their column and row numbers, and the consequent association of true geographic coordinates to them, has led to the calculation of the attitude deviations presented. Such deviations correspond to the average values obtained in an interval of (3 pixels in the row and column numbers (I = I0 $\pm$ 3, J = J0 $\pm$ 3; where I0, J0 are row and column numbers of the identified point), making use of all possible combinations. To each one of all these combinations of “I” and “J”, roll, pitch and yaw angles were calculated. The results of such calculations were supposed normally distributed and, in terms of their mean values and standard deviations, are shown bellow

Roll: (0.035 ± 2.5x10-6)º; pitch: (-0.039 ± 7.1x10-5)º and yaw: (0.432 ± 0.0228)°.

In terms of roll and pitch angles, the magnitude difference between mean values and standard deviations indicate some tolerance in the attitude determination from the identification and pointing of surface characteristics (at least inside the used uncertainty interval: ± 3. The obtained mean results (roll and pitch) exceed the expectations, in the sense that they represent better precision values than that offered by SPOT system (0.15°). The mean yaw value, however, does not match the SPOT system value. In fact, the most precise yaw angle value, 0.11°, obtained inside the (± 3 image units interval, strongly indicates that the pointing tolerance is not that big in terms of yaw angle determination.

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