A SIMPLE APPROACH TO SOLVE THE METEOSAT IMAGE DEFORMATION PROBLEM BASED ON HORIZON EXTRACTION FROM IMAGE DATA AND ORBIT INFORMATION

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ABSTRACT

A method is proposed to determine in a restitution mode METEOSAT image deformations with respect to an image taken under nominal conditions. The approach is based on an iterative procedure for refined determination of the attitude which is derived from northern and southern polar horizon scan limits extracted from infrared image data. Orbit information is supposed to be known with sufficient accuracy.

Keywords: METEOSAT, Attitude refinement, image deformation problem

1. INTRODUCTION

METEOSAT is a spin-stabilized geostationary satellite which takes earth images on a scan line basis; nominally a full earth image is taken with 2500 scan steps at a speed of 100 r.p.m. in up to three spectral channels: infrared, visible and water vapour absorption band.

The image deformation problem consists in finding the relation between earth location of picture elements (pixels) in the actual image and the nominal image, deemed to be taken under ideal nominal conditions.

In order to meet the high accuracy requirements for meteorological data extraction (cloud movement determination), the earth location has to be precise to less than a pixel size, i.e. $4\pi \cdot 10^{-5}$ rad.

2. BASIC ASSUMPTIONS FOR THE DEFORMATION MODEL APPROACH

The actual spacecraft position at any time as derived from ranging measurements by standard flight dynamics procedures is known with sufficient accuracy, i.e. better than 2.5 km for one pixel error.

The radiometer optical axis is describing a cone during one scan line and nutation effects resulting from scan stepping of the telescope can be neglected with good approximation.

For an accurate treatment of the optical axis movement with respect to the attitude, a complicated conglomerate of individual reference frames inside the spacecraft would be needed taking into account all mutual misalignments of mechanical and optical parts which anyhow are known only within certain error margins. Since all these deviations are supposed to be small and since for the image deformation restitution only the net effects are of interest, the angle between optical axis and attitude is approximated by a linear function of radiometer stepping position which is re-adjusted for every image. The movement of the attitude vector between its adjustment for northern and southern horizon scan limits is described by a set of Euler angles being linear functions of time.

The earth surface is sufficiently accurate described by a rotational ellipsoid:

$$\frac{x^2 + y^2}{r_e^2} + \frac{z^2}{r_p^2} = 1, \tag{1}$$

with equatorial radius r_e and polar half axis r_p. Atmospheric effects are taken into account by corresponding adjustment of r_e and r_p.

3. PRINCIPLE IDEA OF REFINED ATTITUDE DETERMINATION FROM HORIZON EXTRACTION OF INFRARED IMAGES

The first and the last radiometer scan position for which the optical axis touches the earth (southern and northern horizon lines) determine two cones for which the corresponding cone angle β between optical axis vector $\vec{o}$ and attitude unit vector $\vec{a} = (a_x, a_y, a_z)$ is given by

$$\beta = \text{arc cos } (\vec{o} \cdot \vec{a}). \tag{2}$$

Let $\vec{t} = (t_x, t_y, t_z)$ be the vector pointing from spacecraft position to the earth tangent point, then

$$\vec{o} = \frac{\vec{t}}{\|\vec{t}\|}, \tag{3}$$

$$\text{with } \|\vec{t}\| = \sqrt{t_x^2 + t_y^2 + t_z^2}. \tag{4}$$

The vectors $\vec{o}$ and $\vec{o} \times \vec{a}$ generate the tangential plane common to the earth surface and the optical axis cone.

The tangential point on the earth is described by a vector

$$\vec{e} = (e_x, e_y, e_z). \tag{5}$$

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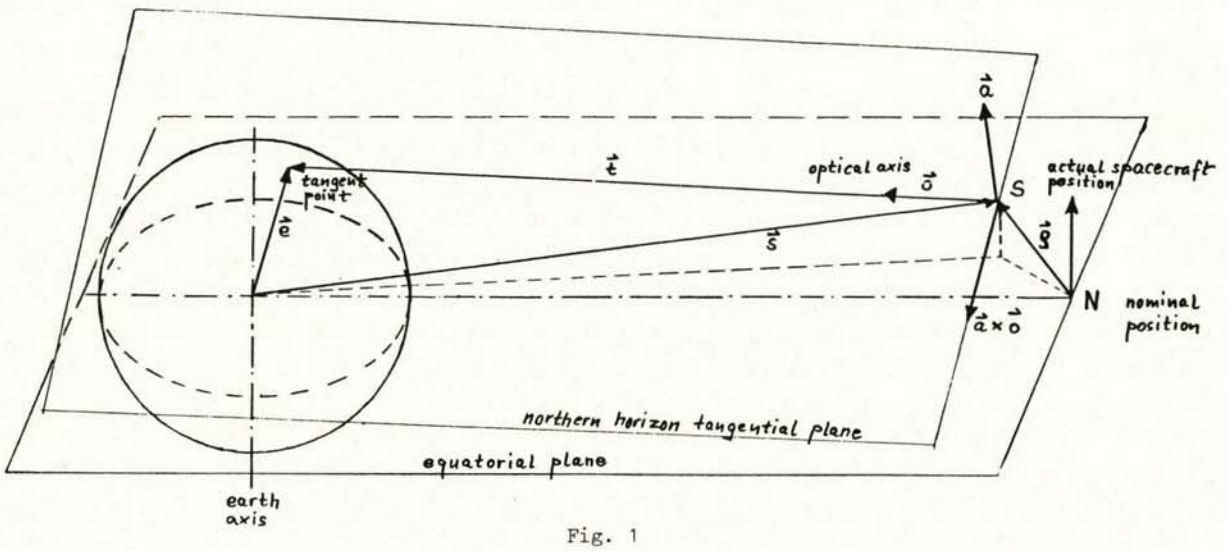

Fig. 1

The spacecraft position vector $\vec{s} = (s_x, s_y, s_z)$ and the vectors $\vec{e}$ and $\vec{t}$ are related by

$$\vec{t} = \vec{e} - \vec{s}. \qquad (6)$$

A third independent point in the tangential plane is given by an arbitrary vector

$$\vec{p} = (p_x, p_y, p_z) = \vec{s} + \vec{t} \times \vec{a}, \qquad (7)$$

or using eq. (6):

$$\vec{p} = \vec{s} + (\vec{e} - \vec{s}) \times \vec{a}. \qquad (8)$$

The coordinates of $\vec{s}$ and $\vec{p}$ obey the equation for the tangential plane

$$\frac{e_x \cdot s_x + e_y \cdot s_y}{r_e^2} + \frac{e_z \cdot s_z}{r_p^2} = 1 \qquad (9)$$

$$\frac{e_x \cdot p_x + e_y \cdot p_y}{r_e^2} + \frac{e_z \cdot p_z}{r_p^2} = 1 \qquad (10)$$

The coordinates of $\vec{e}$ fulfil the ellipsoid equation (1):

$$\frac{e_x^2 + e_y^2}{r_e^2} + \frac{e_z^2}{r_p^2} = 1 \qquad (11)$$

Supposing that the attitude $\vec{a}$ is known from the last refinement step and the satellite position $\vec{s}$ at time of horizon scan is extracted from available orbit information, then the tangential point $\vec{e}$ on earth can be determined by solving the system of equations (9) to (11).

Using equations (6), (3) and (2) the geometrically expected cone angles $\beta_{n.exp}$ and $\beta_{s.exp}$ for northern resp. southern horizon limits can be determined.

From the infrared image data the northern and southern horizon scan positions l_n respectively l_s of the radiometer are isolated. By means of a linear approximation, quasi observed cone angles are derived:

$$\beta_{n.obs} = f_o + f_1 \cdot l_n, \qquad (12)$$

$$\beta_{s.obs} = f_o + f_1 \cdot l_s, \qquad (13)$$

where f_o and f_1 are parameters obtained in the last refinement step. These parameters basically represent the misalignment between the plane of radiometer optical axis stepping movement and the attitude.

The next refinement step is then performed as follows:

Separately from northern and southern horizon limits refined cone angles are determined by taking the mean values

$$\beta_{n.new} = \frac{1}{2}(\beta_{n.exp} + \beta_{n.obs}) \qquad (14)$$

$$\beta_{s.new} = \frac{1}{2}(\beta_{s.exp} + \beta_{s.obs}) \qquad (15)$$

This approach is combined with rotations of the attitude vector $\vec{a}$ around the axes $\vec{o} \times \vec{a}$ by angles

$\frac{1}{2}(\beta_{n.obs} - \beta_{n.exp})$

respectively $\frac{1}{2}(\beta_{s.obs} - \beta_{s.exp})$,

and with a readjustment of parameters f_o and f_1:

$$f_{o.new} = \frac{l_s \beta_{n.new} - l_n \beta_{s.new}}{l_s - l_n}, \qquad (16)$$

$$f_{1.new} = \frac{\beta_{n.new} - \beta_{s.new}}{l_n - l_s}. \qquad (17)$$

Hence, with these new parameters, a relation for transforming radiometer stepping positions into angles relative to the momentary refined attitude is established which consistently fulfils the boundary conditions for northern and southern horizon limits.

The proposed attitude refinement procedure compensates first for roll angle uncertainties whereas yaw angle deviations are not directly covered. But since the attitude adjustment procedure is applied on successive images, yaw angle deviations will converge after a quarter of the orbit to the order of magnitude for the roll angle determination error.

4. METHOD OF DEFORMATION MODEL CALCULATIONS

4.1 The general concept

After reception of a full image scan positions for upper and lower horizon bounds, l_n and l_s, are extracted from the infrared image data. These scan positions are uniquely related to time and hence from orbit information the corresponding spacecraft position $\vec{s}$ in the mean geocentric system is obtained.

In order to make use of the rotational symmetry of the geometry, coordinates of $\vec{s}$ and $\vec{a}$ are transformed by plane rotation to a system where the y-component of the spacecraft position is zero.
This allows to simplify the system of equations (9) to (11) and to transform it into a polynomial of order 4 for the component e_z. Since under normal satellite conditions the attitude is close to the earth axis direction, the corresponding roots of the polynomial can easily be determined by a NEWTON iteration. The starting value for this iteration is obtained by inserting the nominal attitude (z-component = 1) into the polynomial which reduces it to a quadratic equation. Then the iteration usually converges within few steps.

Having found by this method the tangent point vector $\vec{e}$, coordinates are transformed back to the mean geocentric system. The corresponding cone angles are calculated and the adjustment of the attitude performed by rotation $\frac{1}{2}(\beta_{obs} - \beta_{exp})$ around axis $\vec{\sigma} \times \vec{a}$. The refined attitude from southern horizon is used as input for the northern horizon refinement step.

For the description of image deformation another set of convenient coordinate systems is used (figure 2):

- the nominal image frame (NIF) with origin at nominal satellite position N
  x_n-axis pointing towards the earth centre and $z_n = 0$ being the equatorial plane
- the actual image frame (AIF)
  with origin at momentary satellite position S
  x_a-axis pointing towards the earth, the earth centre being in the plane $y_a = 0$ and z_a-axis coinciding with the refined attitude $\vec{a}$.

For the same point P on earth the relations between coordinates are:

$$\vec{r}_n = \vec{\rho} + R \cdot \vec{r}_a, \qquad (18)$$

$$\vec{r}_a = R^T (\vec{r}_n - \vec{\rho}), \; R^T = R^{-1}, \qquad (19)$$

where R is the orthogonal transformation given by the matrix

$$R = \begin{pmatrix} \cos\gamma\cdot\cos\delta & -\sin\gamma\cdot\cos\varepsilon + \cos\ \cdot\sin\ \cdot\sin & \sin\gamma\cdot\sin\varepsilon + \cos\ \cdot\sin\ \cdot\cos \\ \sin\gamma\cdot\cos\delta & \cos\gamma\cdot\cos\varepsilon + \sin\gamma\cdot\sin\delta\cdot\sin\varepsilon & -\cos\gamma\cdot\sin\varepsilon + \sin\gamma\cdot\sin\delta\cdot\cos\varepsilon \\ -\sin\delta & \cos\delta\cdot\sin\varepsilon & \cos\delta\cdot\cos\varepsilon \end{pmatrix} \qquad (20)$$

with $\gamma, \delta, \varepsilon$ being Euler angles as usual.

Since the time of northern and southern polar horizon scans is known, the corresponding vectors for spacecraft position and refined attitude are transformed into the nominal image frame.

The spacecraft offset vector $\vec{\rho}$ with respect to NIF is then approximated by a polynomial of radiometer scan step which is fitted to the time dependence of $\vec{\rho}$.

For the image deformation calculation the time dependence of the AIF is needed. Since this frame is supposed to be fixed during a scan step, it will be sufficient to express the transformation matrix R by functions of radiometer scan step.

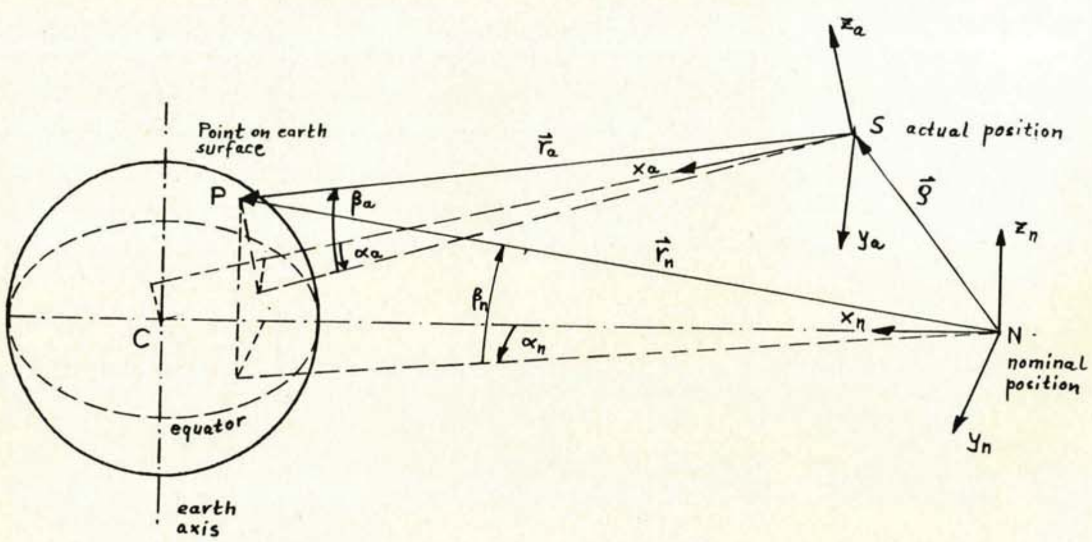

Figure 2: Coordinate systems for description of image deformations.
The earth centre C is always in the planes $y_a = 0$ and $y_n = 0$.

From the condition z_a-axis parallel $\vec{a}$ and the phase condition (earth centre in plane y_a), one obtains a set of equations:

$$a_x = \sin\gamma \cdot \sin\varepsilon + \cos\gamma \cdot \sin\delta \cdot \cos\varepsilon, \quad (20)$$

$$a_y = -\cos\gamma \cdot \sin\varepsilon + \sin\gamma \cdot \sin\delta \cdot \cos\varepsilon, \quad (21)$$

$$a_z = \cos\delta \cdot \cos\varepsilon, \quad (22)$$

$$(H - \rho_x)(-\sin\gamma \cdot \cos\varepsilon + \cos\gamma \cdot \sin\delta \cdot \sin\varepsilon)$$
$$- \rho_y (\cos\gamma \cdot \cos\varepsilon + \sin\gamma \cdot \sin\delta \cdot \sin\varepsilon)$$
$$- \rho_z \cos\delta \cdot \sin\varepsilon = 0, \quad (23)$$

where a_x, a_y, a_z are the attitude components in NIF, ρ_x, ρ_y, ρ_z are the components of the satellite offset vector $\vec{\rho}$ in NIF and H is the nominal height of the spacecraft above earth centre.

For an accurate treatment, Euler angles for northern and southern horizon boundary conditions have to be determined by solving the system of equations (20) to (23). But since attitude deviations from nominal value are supposed to be smaller than part of a degree and being inline with the inherent accuracy of the whole approach, a linearisation of the transformation matrix R seems to be adequate.

For γ, δ, ε less than 1 degree the error amounts to the order of one pixel at most. Calling R_1 the linearised approximation, the transformation becomes

$$R_1 = \begin{pmatrix} 1 & -\gamma & \delta \\ \gamma & 1 & -\varepsilon \\ -\delta & \varepsilon & 1 \end{pmatrix} \quad (24)$$

Hence, γ, δ, ε are obtained from the attitude components and the phase condition:

$$\delta = a_x \quad (25)$$

$$\varepsilon = -a_y \quad (26)$$

$$\gamma = \frac{\varepsilon \rho_z - \rho_y}{\rho_x - H} \quad (27)$$

Determining δ_n, ε_n, γ_n and δ_s, ε_s, γ_s for the northern and southern horizon limit, the time dependence of the Euler angles is expressed as function of radiometer scan step l:

$$\gamma = \gamma_o + \gamma_1 \cdot l \text{ with } \gamma_o = \frac{\gamma_n l_s - \gamma_s l_n}{l_s - l_n} \text{ and } \gamma_1 = \frac{\gamma_n - \gamma_s}{l_n - l_s} \quad (28)$$

$$\delta = \delta_o + \delta_1 \cdot l \text{ with } \delta_o = \frac{\delta_n \cdot l_s - \delta_s \cdot l_n}{l_s - l_n} \text{ and } \delta_1 = \frac{\delta_n - \delta_s}{l_n - l_s} \quad (29)$$

$$\varepsilon = \varepsilon_o + \varepsilon_1 \cdot l \text{ with } \varepsilon_o = \frac{\varepsilon_n l_s - \varepsilon_s \cdot l_n}{l_s - l_n} \text{ and } \varepsilon_1 = \frac{\varepsilon_n - \varepsilon_s}{l_n - l_s} \quad (30)$$

With this approximation of Euler angles the relative movement of the actual image frame AIF with respect to NIF is determined for each scan step of the actual image.

Picture elements (pixels) are usually addressed by row number i and column number k which are related to elevation angle β and azimuth α by means of stepping angle and sampling rate respectively.

In the nominal image the relations are

$$\alpha_n = q_n \cdot k_n - 1250.5, \quad (31)$$

$$\beta_n = q_n \cdot i_n - 1250.5, \; q_n = 4\pi \cdot 10^{-5}, \quad (32)$$

observing that pixel addressing starts at south-east corner. In the actual image conversion factors are in general functions of scan step l

$$\alpha_a = q_{a.\alpha}(l) \; k_a - 1250.5, \quad (33)$$

$$\beta_a = f_{1.new} \; i_a - 1250.5. \quad (34)$$

The column step angle is affected by spin speed variations which can be approximated by a quadratic function of l fitted to each image. For consistency in addition to timing information the equatorial horizon extraction is used to adapt $q_{a.\alpha}(l)$.

The row stepping angle $f_{1.new}$ is taken from equation (17).

The deformation calculations are twofold:

- the direct problem consists in finding pixel coordinates in the actual image when pixel coordinates in the nominal image are known;
- the inverse problem requires to find pixel coordinates in the nominal image while those of the actual image are known.

4.2 <u>The direct deformation calculations</u>

From pixel address i_n, k_n the angles α_n, β_n are derived. The corresponding stepping position in the actual image is approximated by

$$l = i_n + \frac{l_n + l_s}{2} - 1250.5, \quad (35)$$

where l_n and l_s are obtained from horizon extraction.

The point P on earth surface is given by the vector $\vec{r}_n$ with components

$$x_n = r_n \cdot \cos\alpha_n \cdot \cos\beta_n, \quad (36)$$

$$y_n = r_n \cdot \sin\alpha_n \cdot \cos\beta_n, \quad (37)$$

$$z_n = r_n \cdot \sin\beta_n, \quad (38)$$

$$\text{with } r_n = \|\vec{r}_n\|. \quad (39)$$

From the condition that P is on the ellipsoid, i.e.

$$\frac{(H - x_n)^2 + y_n^2}{r_e^2} + \frac{z_n^2}{r_p^2} = 1, \quad (40)$$

r_n can be calculated (taking the minor root):

$$r_n = \frac{B - \sqrt{B^2 + AC}}{A}, \quad (41)$$

$$\text{where } A = \cos^2\beta_n + \left(\frac{r_e}{r_p}\right)^2 \sin^2\beta_n, \quad (42)$$

$$B = \cos\alpha_n \cdot \cos\beta_n \cdot H, \quad (43)$$

$$C = r_e^2 - H^2. \quad (44)$$

Using the transformation matrix $R_1(l)$ and the satellite offset $\vec{\varrho}(l)$ as functions of l, the vector $\vec{r}_a$ is obtained with relation (19):

$$\vec{r}_a = R_1^T(l)\,(\vec{r}_n - \vec{\varrho}(l)), \quad (45)$$

hence,

$$\alpha_a = \arctan\left(\frac{y_a}{x_a}\right), \quad (46)$$

$$\beta_a = \arctan\left(\frac{z_a}{\sqrt{x_a^2 + y_a^2}}\right). \quad (47)$$

Pixel coordinates in the actual image are then derived by means of eqs. (33) and (34). If accuracy requires it a refined scan position l based on the resulting i_a can be fed into eq. (45) for a further iteration step.

4.3 The inverse deformation calculation

The scan step l is simply given by actual image line number i_a plus the scan offset at image start:

$$l = i_a + l_{start}. \quad (48)$$

From pixel coordinates i_a, k_a the angles α_a, β_a are derived with eqs. (33), (34) and $\vec{r}_a$ is expressed by

$$x_a = r_a \cdot \cos\alpha_a \cdot \cos\beta_a, \quad (49)$$

$$y_a = r_a \cdot \sin\alpha_a \cdot \cos\beta_a, \quad (50)$$

$$z_a = r_a \cdot \sin\beta_a,\ r_a = \left|\vec{r}_a\right|. \quad (51)$$

Relation (18) then reads:

$$x_n = \varrho_x^{(l)} + r_a \cdot E, \quad (52)$$

$$y_n = \varrho_y^{(l)} + r_a \cdot F, \quad (53)$$

$$z_n = \varrho_z^{(l)} + r_a \cdot G, \quad (54)$$

where

$$E = \cos\alpha_a \cdot \cos\beta_a - \gamma(l)\cdot\sin\alpha_a\cdot\cos\beta_a + \delta(l)\cdot\sin\beta_a, \quad (55)$$

$$F = \gamma(l)\cos\alpha_a\cdot\cos\beta_a + \sin\alpha_a\cdot\cos\beta_a - \varepsilon(l)\sin\beta_a, \quad (56)$$

$$G = -\delta(l)\cos\alpha_a\cdot\cos\beta_a + \varepsilon(l)\sin\alpha_a\cdot\cos\beta_a + \sin\beta_a. \quad (57)$$

From the condition that $\vec{r}_a$ points onto the ellipsoid r_a is derived by means of equation (40):

$$r_a = \frac{L - \sqrt{L^2 + KM}}{K}, \quad (58)$$

where

$$K = E^2 + F^2 + \frac{r_e^2}{r_p^2} G^2, \quad (59)$$

$$L = E(H - \varrho_x) - F\varrho_y - \frac{r_e^2}{r_p^2} G\varrho_z, \quad (60)$$

$$M = r_e^2 - (H - \varrho_x)^2 - \varrho_y^2 - \frac{r_e^2}{r_p^2}\varrho_z^2. \quad (61)$$

Having calculated the components of $\vec{r}_n$, the pixel coordinates in the nominal image are then given by means of

$$\alpha_n = \arctan\left(\frac{y_n}{x_n}\right), \quad (62)$$

$$\beta_n = \arctan\left(\frac{z_n}{\sqrt{x_n^2 + y_n^2}}\right), \quad (63)$$

and eqs. (31) and (32).

5. REFINEMENT OF THE DEFORMATION MODEL

5.1 Radiometer misalignment

The heuristic approach for attitude adjustment as outlined in paragraph 3 allows for a consistent treatment of deformations within one image, but does not isolate a systematic radiometer misalignment with respect to the attitude. In order to achieve this, a long-term analysis of the cone angle differences $\beta_{obs} - \beta_{exp}$ (see eqs. (2), (12) and (13)) is performed and Euler angles of a radiometer related reference frame with respect to a mean attitude can be approximated by a least squares fit.

5.2 Automatic landmark extraction

In order to achieve a deformation determination accuracy up to parts of a pixel additional earth location information is needed. A set of landmarks adequately spread over the field of view and suitable for automatic correlation is selected.
A landmark catalogue is built based on real image data together with the exact geographical position.

By means of numerical correlation as outlined in reference (4) or reference (5), the displacements of landmarks between nominal and actual image are derived. For each successful landmark correlation a set of "experimental" Euler angles $\gamma, \delta, \varepsilon$ can be determined using the linearised form R_1 of the transformation matrix. Assigning in addition a landmark quality weighting factor, these values are then used for a least squares fit of the Euler angles as polynomials of radiometer scan step.

6. CONCLUSION

Making use of the fact that METEOSAT dynamical behaviour during image taking process is smooth and that deviations can be sufficiently accurate parameterised by linear or quadratic functions, and based on the experience that northern and southern horizon scan limits can well be identified from infrared image data, it is possible to derive a fairly accurate deformation model.

This deformation model is basically characterised by an actual image related reference frame for which offset and direction with respect to a nominal image frame are given as functions of radiometer scan step.

The user of METEOSAT images provided with the few necessary parameters can apply this model by means of a pocket calculator at any image point of the earth with the same order of accuracy.

There are no numerical problems as occurring with the former deformation model (see ref. 3) where an interpolation scheme with fifth order polynomials had to be applied.

When restricting to attitude adjustment based on northern and southern polar horizon scans the computational effort for deriving the model parameters is negligible compared with the former model. Only inclusion of automatic landmark registration will count for a significant contribution in computer time.

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