ENCODER IN-ORBIT CALIBRATION OF THE MTG SCANNER

Antonio González Elías (1), Cristina Tato Ribera (1), Sergio Reguero Cachafeiro (1), Laurent Bouyeron (2)

(1) SENER Ingeniería y Sistemas, Severo Ochoa, 4, 28760 Tres Cantos-Madrid (Spain), antonio.gonzalezelias@sener.es
(2) CODECHAMP 23190 Champagnat – France, 1 La Chaudure, l.bouyeron@codechamp.fr:

ABSTRACT

SENER is responsible for the MTG scanner, which implements the scanning function of the M0 mirror on a two axes gimbal. The performance requirements on this system are quite demanding in terms of pointing, knowledge and exported torques. One of the key elements for achieving those requirements is the encoder, which produces the angular measurements. The selected encoder for both axes is a 25-bit encoder by CODECHAMP, which provides the highest resolution and accuracy available at that moment. However, the raw accuracy of the encoder is not enough to reach the exacting requirements, even considering on-ground calibration. This paper presents a technique to perform the encoder calibration in-orbit. This approach avoids the limitations of the on-ground characterization, and may be performed periodically in-orbit to limit the aging effects.

1. INTRODUCTION

Meteosat Third Generation (MTG) programme has been established through cooperation between ESA and EUMETSAT. This programme will provide access to space-acquired data for meteorological purposes. The mission will encompass two different satellite concepts, the MTG-I imager and the MTG-S sounder, hosting different payloads: Flexible Combined Imager (FCI) and Infrared Sounder (IRS) instruments, respectively.

SENER, with OHB Systems (Munich) as direct customer, is responsible for MTG Scan Assembly (MTG-SCA), which constitutes the subsystem in charge of the scanning function of M0 mirror of both instruments.

The scanner provides a two-axis gimbal mounted on flexural pivots [1] to control M0 mirror pointing. Each axis includes a 25-bit absolute encoder manufactured by CODECHAMP to monitor the scanner pointing. The high resolution of this encoder is achieved by the interpolation of two sinusoidal signals in quadrature. Unfortunately, the imperfections of these signals, caused by different effects (e.g. off-centring, rotor-stator airgap, thermal effects and radiation), induce periodic errors that are commonly known as encoder harmonics [2].

The initial performance analyses showed that the on-ground calibration was not sufficient to guarantee the scanner performances over its full operational life. First, the harmonics have significant sensitivity to the encoder off-centring and rotor airgap. Therefore, the effectivity of on-ground characterisation is limited by gravity effects and the launch loads. Second, the ageing effects on the encoder electronics will also induce a variation on the harmonics over time that will degrade the end-of-life performance.

Fortunately, SENER has developed an in-orbit calibration of the encoder with the support of Thales Alenia Space (Cannes), Airbus Defense and Space (Toulouse) and CODECHAMP. The encoder in-orbit calibration is crucial to reach the challenging SCA performance requirements. The main benefits are, first, that it is not limited by gravity effects and launch loads, and second, that the calibration can be performed periodically (every 6 months as baseline) to mitigate ageing effects.

The information on this paper has been organized in three main blocks. After this introduction, the section “Problem understanding” provides the main elements to understand the harmonics’ nature, their impact on the performance and the role of calibration. The following section, “SENER solution of the in-orbit calibration”, explains in detail the in-orbit calibration, which is split in three parts: the operation definition (how to gather the data), the harmonics extraction (how to get the harmonics from the data), and the harmonics correction (how to remove the harmonics). And finally, the section “Validation of the in-orbit calibration” shows the activities performed to assess the effectiveness of the in-orbit calibration. It includes analysis and test activities.

Before going into details, it is worth noting the units used in this paper for the angular quantities. Encoder rotations and velocities are expressed in degrees (º) and degrees per seconds (º/s) respectively. In contrast, encoder errors and harmonics are small quantities and are expressed in microradians (µrad).

2. PROBLEM UNDERSTANDING

2.1. Harmonics Description and Definition

The encoder presents a high frequency error that has a periodic nature in the spatial domain. This error can be decomposed into a number of sinusoids called harmonics. Fig. 1 gives an illustrative example of the encoder error decomposition into harmonics. In this case, there are two harmonics that are identified by their equivalent bit period: BIT#14 and BIT#16. This way of naming the harmonics and other relevant aspects of encoder harmonics are explained in detail in this subsection.

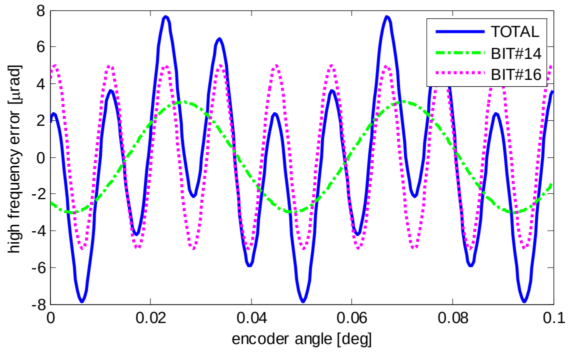

Figure 1. Encoder high frequency error and decomposition into harmonic components

To understand the harmonic representation, it is important to consider first the role of the bits in the angle codification (see Fig. 2). The scanner employs a 25-bit absolute CODECHAMP encoder. This means that the encoder divides one turn (360º) in 2^{25} angular sectors, and provides a unique 25-bit word for each sector. Therefore the resolution of the encoder is $1/2^{25}$ of a turn (= $360/2^{25}$deg = $2\pi/2^{25}$rad ≈ 0.187µrad).

There are two ways to refer to a particular encoder bit: the word index and the bit number. The word index refers to position of the bit within the encoder word. The LSB ("Least Significant Bit") has INDEX#0, and the MSB ("Most Significant Bit") has INDEX#24. The bit number refers to the spatial period of a particular bit. For instance, the BIT#1 has a period of 360º; it is equal to '0' from 0º to 180º, and '1' from 180º to 360º. Fig. 2 illustrates the correspondence between word indexes and bit numbers, and the bit periods.

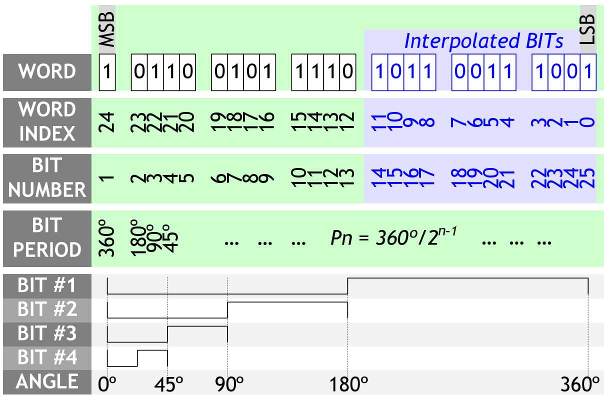

Figure 2. Encoder word, bits and bit periods

Out of the 25bits of the encoder, the bits from BIT#1 to BIT#13 are engraved on the encoder disk, while the bits from BIT#14 to BIT#25 are interpolated from two sinusoidal signals (sine / cosine) of BIT#14-period (fine track, see Fig. 3).

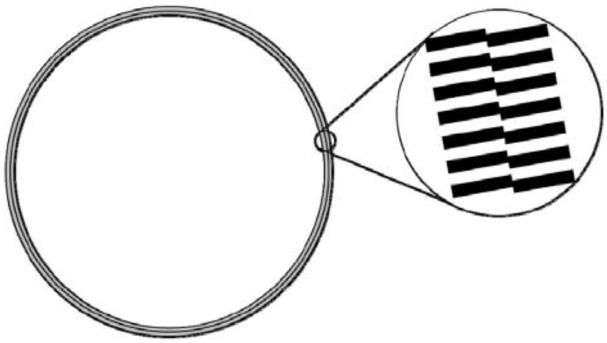

Figure 3. Schematic view of the encoder fine track

The encoder harmonics have two origins:

1. The interpolation errors caused by the sine / cosine signals imperfections: offsets, differential amplitude and waveform errors.
2. The crosstalk between the fine track signals and the BIT#13 signal.

The BIT#13 crosstalk error will generate the harmonic with the longest period ($P_{13}=360º/2^{13-1}$=87.9mdeg). The period of the rest of the harmonics will be an integer fraction of the BIT#13 period. This is the same concept as the Fourier series decomposition of a periodic signal (see [3]).

HAR. k [#]	**HAR. PERIOD $P_k = P_{14}/k$ [mdeg]**	**EQUIVALENT BIT $n = 1+\log_2(360º/P_k)$ [bit]**
0.5	87,9	13
1.0	**43,9**	**14**
1.5	**29,3**	**14,58**
2.0	**22,0**	**15**
2.5	17,6	15,32
3.0	**14,6**	**15,58**
3.5	12,6	15,81
4.0	**11,0**	**16**
4.5	9,8	16,17
5.0	8,8	16,32
5.5	8,0	16,46
6.0	7,3	16,58
6.5	6,8	16,70
7.0	6,3	16,81
7.5	5,9	16,91
8.0	**5,5**	**17**

Table 1. Encoder harmonics and equivalent bit

Tab. 1 shows the harmonic period (P_k) and the equivalent bit (n) for the first sixteen harmonics. The "k" value represents the number of periods of the harmonic within one period of BIT#14 ($P_{14}=360º/2^{14-1}$=43.9mdeg). For example, the harmonic k=3 (BIT#15.58) will have 3 complete periods within one period of BIT#14. It is worth noticing that BIT#14 is used as reference (instead of BIT#13) because it defines the size of the fine track, i.e. the period of the sine / cosine signals.

In general, the equivalent bit (BIT#n) is used to identify the harmonics. As it is shown in Tab. 1, some harmonics present a non-integer equivalent bit (e.g. BIT#14.58). In fact, only the harmonics that are a power of two ($k=2^x$) present an integer equivalent bit (n), the rest are non-integers. In addition, not all the harmonics contribute significantly to the high frequency error. This table highlights the most relevant contributors according to test results.

According to this definition, the high frequency error (e_{HF}) can be decomposed as the sum of the harmonics (h_n):

$$e_{HF} = \sum h_n \tag{1}$$

And each harmonic (h_n) can be defined by the following expression:

$$h_n = H_n \cdot \sin(2^{n-1} \cdot p + q_n) \tag{2}$$

where p is the encoder angle, H_n is the harmonic amplitude, q_n is the relative phase, and n is the equivalent harmonic bit.

If the encoder moves at constant speed (v):

$$p = v \cdot t \tag{3}$$

where t is the time variable, then the encoder harmonics are seen at a constant temporal frequency (f_n):

$$h_n = H_n \cdot \sin(\underbrace{2^{n-1} \cdot v}_{360^{\circ} f_n} \cdot t + q_n) \tag{4}$$

Thus, the temporal frequency depends linearly on the velocity:

$$f_n = \frac{2^{n-1}}{360^{\circ}} \cdot v \tag{5}$$

where the velocity v has been expressed in [º/s]. This expression will be useful later for the development of calibration concept.

2.2. Harmonics of the Encoder Mounted on Flexural Pivots

The encoder harmonics are first characterized at CODECHAMP facilities. To emulate the scanner conditions, the encoder is mounted on flexural pivots. The test set-up is shown in Fig. 4.

The procedure for harmonic characterization is based on a free-oscillation movement. This is illustrated in Fig. 5 with the data gathered from the engineering model (EM). The rotation of the encoder is limited by the flexural pivot in the range of ±11.25º, and the oscillation period is 3.2 seconds. The data is then sampled at 15 kHz and post-processed to extract the harmonic content.

Figure 4. Test setup for harmonic identification at CODECHAMP facilities

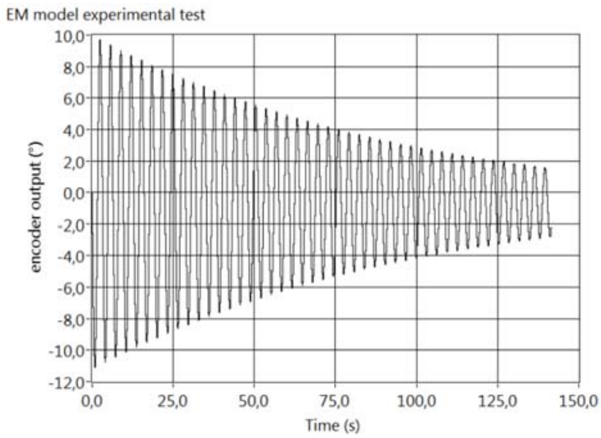

Figure 5. Encoder recording of a free oscillation movement

The free-oscillation extraction algorithm has been developed and validated by CODECHAMP. The algorithm is based on a sliding average window. The length of the window (i.e. the number of samples) is selected to separate the actual movement (the damped sinusoid of the free oscillation), at low frequency, from the fictitious movement (the encoder harmonics), at high frequency. As a result, the harmonics can be represented in the spatial domain, where the horizontal axis is the actual angle and the vertical axis is the harmonic error (see Fig. 7, 8 and 9). This curve is frequently referred to as the "encoder fingerprint error".

This procedure, based on free oscillation, is fairly simple but quite effective, as shown by the tests evidences. For this reason, it is the baseline for on-ground characterization at CODECHAMP (encoder level) and also at SENER (scanner level). Unfortunately, the same procedure cannot be applied for in-orbit calibration, due to the fact that the in-orbit data is corrupted by the microvibration environment. This motivates the development of a more complex procedure for the in-orbit calibration that is explained in the next section.

The harmonic error of the encoder mounted on flexural pivots is shown in Fig. 9. It presents a significant amplitude modulation over the angular range. Additionally, this modulation reduces its period as the encoder moves from the middle to the extremes of the angular range. This behaviour is due to the centre's shift induced by the rotation of the flexural pivots. The justification is illustrated in Fig. 7 and Fig. 8. These figures show the harmonic error of the encoder mounted on ball bearings. Fig. 7. shows the harmonic content without off-centring, and Fig. 8., with a 100µm radial off-centring. It can be seen that the off-centring produces an amplitude modulation of the harmonics. The general formula of the amplitude modulation is the following:

$$A(p) = A_{B16} \cdot \left|\cos\left(360º \cdot \frac{\Delta x(p)}{0.25 \cdot sw_{B14}}\right)\right| + A_x \qquad (6)$$

where A_{B16} is the amplitude of BIT#16 without off-centring (see Fig. 7), $\Delta x(p)$ is the projection of the off-centring on the direction perpendicular to the reading slots of the fine track (a sine for a circular motion), sw_{B14} is the slot width of the fine track, and A_x is the average value of the amplitude.

When the encoder is mounted on flexural pivots, the centre's shift varies with the rotation in a parabolic fashion [1], and this justifies the variation of the modulation period observed in Fig. 9.

The amplitude modulation indicates that the harmonic content varies within the angular range. Fig. 6 and Fig. 10 illustrate the content and variation of the harmonic components. The latter, Fig. 10, shows a three dimensional plot of the harmonic content. One horizontal axis represents the angular range, and the other, the harmonic spatial frequency, which is expressed by the equivalent bit (see Tab. 1). It shows that the harmonic content is distributed among a few number of spatial frequencies: BIT#14, BIT#14.58, BIT#15, BIT#15.58, BIT#16 and BIT#17. In particular, BIT#16 harmonic is the major contributor. In fact, it is the responsible of the amplitude modulation. This is even clearer in Fig. 6 where the contribution of the significant harmonics are compared over the angular range. The amplitude variation of BIT#16 corresponds to amplitude modulation of Fig. 9.

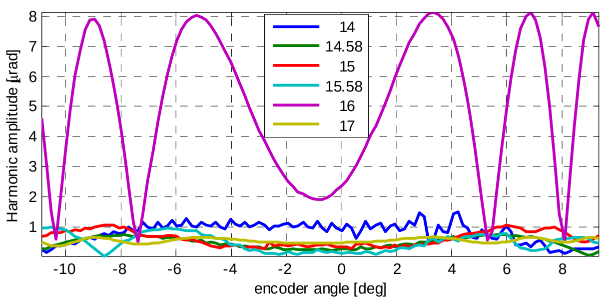

Figure 6. Harmonic amplitude variation

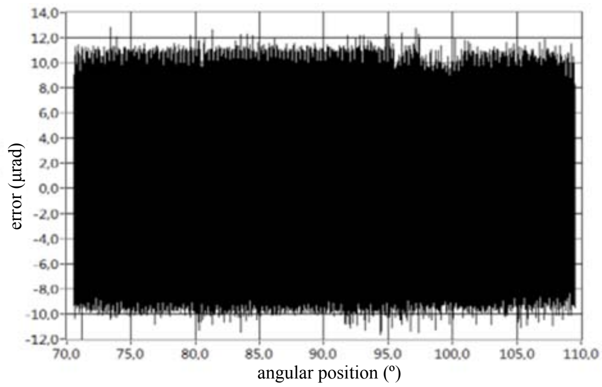

Figure 7. Harmonics on bearings without off-centring

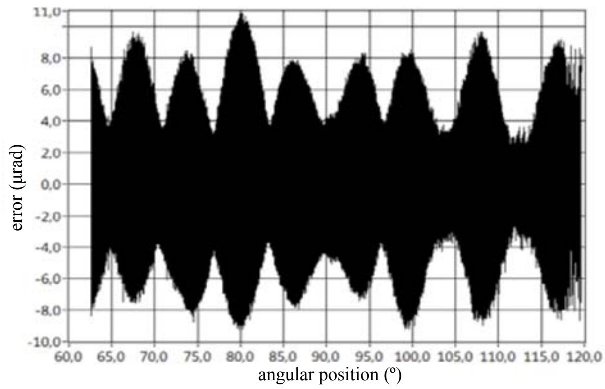

Figure 8. Harmonics on bearings w. 100µm off-centring

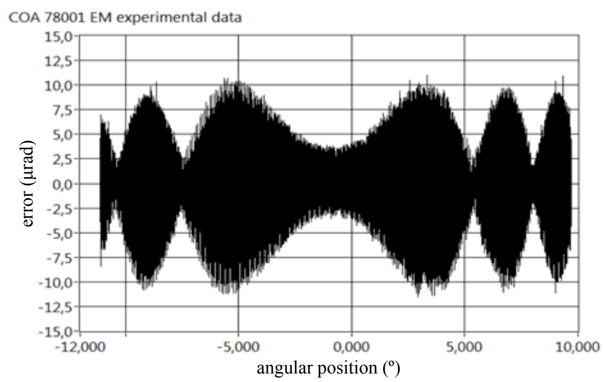

Figure 9. Harmonics mounted on flexural pivots

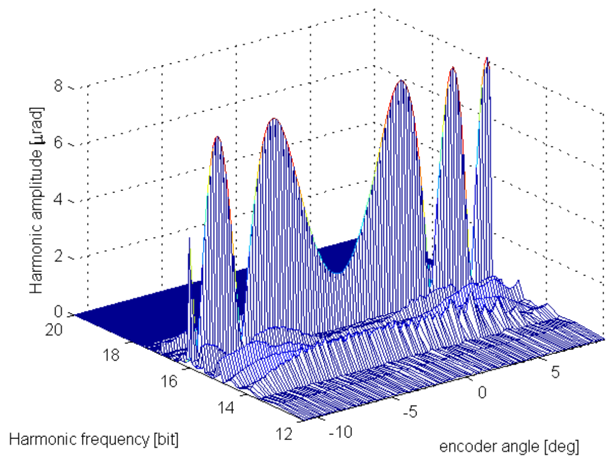

Figure 10. Harmonics content and variation

2.3. Calibration to Improve SCA Performances

The encoder harmonics have a direct impact on the scanner performance, in particular in the following three aspects: knowledge, pointing and exported torques (see Fig. 11).

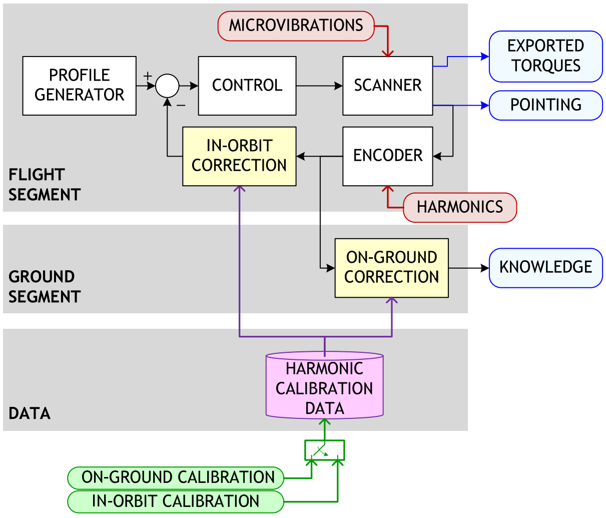

Figure 11. Harmonic calibration to improve SCA performances

The knowledge error is defined as the difference between actual and estimated pointing. Harmonics are in essence accuracy errors of the encoder, and thus they have a direct impact on the pointing knowledge of the scanner.

Moreover, as the encoder closes the pointing control loop (see Fig. 11), the harmonics also affect the actual pointing and the exported torques of the scanner. In this case the impact is not direct, since it depends on the closed loop dynamics including the control and the scanner.

Fortunately, this error is repetitive and it can be characterized and corrected. Two calibrations are foreseen for the harmonics (see Fig. 11):

1. On ground (O. G.) calibration at SCA level: the encoder is characterized at unit level by CODECHAMP, and at SCA level after encoder integration by SENER. The harmonics extraction is based on a free oscillation (see Section 2.2). This calibration provides the BoL (Beginning of Life) harmonics data for O.G and I.O. correction.
2. In orbit (I. O.) calibration at SCA level: Due to ageing and radiation the encoder harmonics need to be calibrated in orbit. The scanner includes a specific configuration (sampling, control, motion profiles) for the calibration. The operation data is downloaded to ground to extract the harmonics, and this information is used to update O.G. and I.O. correction data. This is explained in detailed in Section 3.

Fig. 11 summarizes the calibration concept. There are two corrections: one in-orbit (flight segment), and one on-ground (ground segment). The in-orbit correction is developed to improve the actual pointing and the exported torques. It has limited resources as it is implemented on-board. The on-ground correction is developed to improve the pointing knowledge. As mentioned above, the calibration data might have two origins: on-ground or in-orbit.

3. SENER SOLUTION FOR THE IN-ORBIT CALIBRATION

The in-orbit calibration process can be divided in three main parts (see Fig. 12):

1. Operation definition: it defines the scanner configuration for the in-orbit calibration. It includes the following aspects: the encoder sampling frequency, the motion profiles and the control.
2. Harmonics extraction: it defines the algorithms to estimate the harmonics from the available data.
3. Harmonics correction: it defines the algorithms to correct the harmonics in-orbit and on-ground.

These three parts are interconnected, since the definition of one part affects the definition of the others. As a result the in-orbit development is an iterative process that takes into account the calibration needs and constraints.

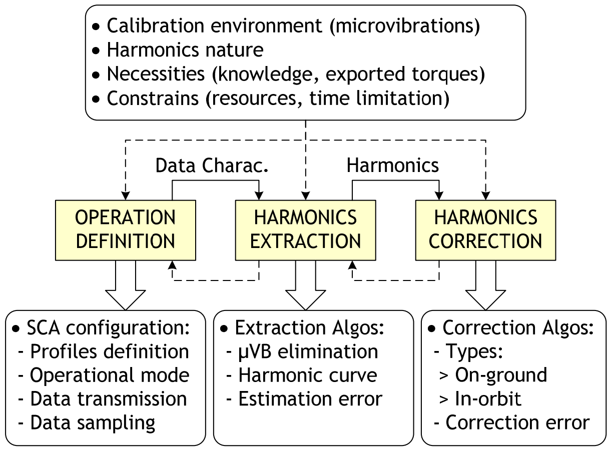

Figure 12. Parts of the in-orbit encoder calibration

3.1. Scanner Operation

The operation defines the scanner configuration for the in-orbit calibration, including how to move the scanner (motion profiles) and how to gather the data (sampling).

One aspect that is of particular relevance is the microvibration environment. Fortunately, the encoder can be calibrated in a more favourable environment than the operational one. This can be achieved by scheduling the in-orbit calibration for particular satellite operations where the microvibrations are reduced in the range of interest. The assumed calibration environment considers a microvibration-free range from 0Hz to 10Hz.

The in-orbit calibration is based only on the encoder measurements, which combine the actual motion of the encoder and the fictitious motion of its harmonics. Moreover, the actual motion is due to the motor currents and the microvibration environment. An illustrative scheme of the system is shown in Fig. 11 where the microvibrations and the harmonics are depicted as external inputs. Now the question is how to isolate the harmonic errors (fictitious) from the actual movement, in particular from the microvibrations. Eq. 5 indicates that temporal frequency of the harmonics (f_n) can be manipulated by the scanner speed (v). Thus, the velocity can be used to isolate in the frequency domain the harmonics from the microvibrations. Based on this idea, two different motion alternatives were traded-off:

1. Free Oscillation
2. Constant velocity profiles

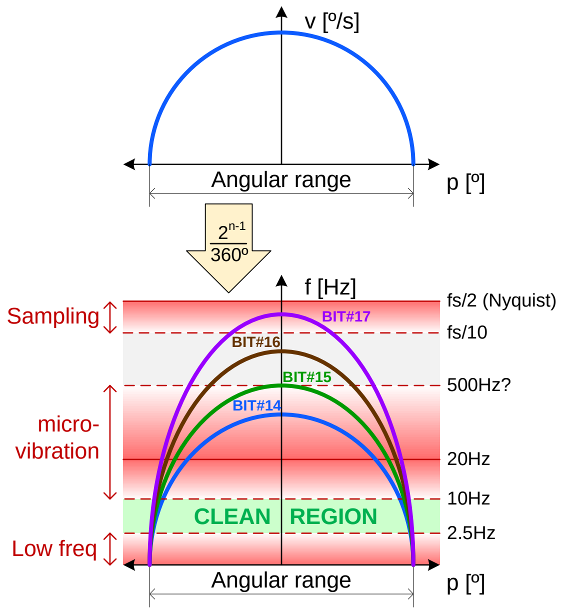

Figure 13. Harmonics isolation for the free oscillation

The free-oscillation movement is explained in Section 2.2. The position-velocity map of the free oscillation can be used to study the harmonic frequency content. This is shown in Fig. 13. The velocity is transformed into the harmonic frequencies by applying Eq. 5. This figure also illustrates graphically the frequency limitations for the harmonics identification. At very low frequencies (below 2.5Hz in the SCA case), the harmonics could be confused with the motion of the scanner. At medium frequencies (above 10Hz), the microvibrations might corrupt the harmonic content. And at high frequencies, the sampling frequency (fs) limits the maximum frequency that can be identified. Between the low frequencies (2.5Hz) and the microvibrations (10Hz) there is a clean region that is appropriate for identification. There might be also a region before the sampling limit where the microvibrations are not significant, but its size and cleanliness is difficult to assess. In free-oscillation, the harmonic frequencies are mostly outside the clean region (2.5Hz-10Hz) over the angular range; this is the reason why this option is disregarded for the in-orbit calibration.

The proposed approach to locate the harmonics in the clean region (2.5Hz-10Hz, see Fig. 13) consists in moving the scanner at low constant speeds. It is not possible to identify all the relevant harmonics at one speed; thus, the motion is repeated at several speeds (see Fig. 14). Tab. 2 provides the proposed speeds and indicates the harmonics that are identified at each one (green cells).

	Speeds		
	v_1 = 0.22 º/s	**v_2 = 0.1 º/s**	**v_3 = 0.042 º/s**
BIT#17	40.05	18.20	**7.65**
BIT#16	20.02	**9.10**	**3.82**
BIT#16.58	15.02	**6.83**	**2.87**
BIT#15	10.01	**4.55**	1.91
BIT#14.58	**7.51**	**3.41**	1.43
BIT#14	**5.01**	2.28	0.96
BIT#13	**2.50**	1.14	0.48

Table 2. Frequency of the harmonics in Hz for each calibration speed.

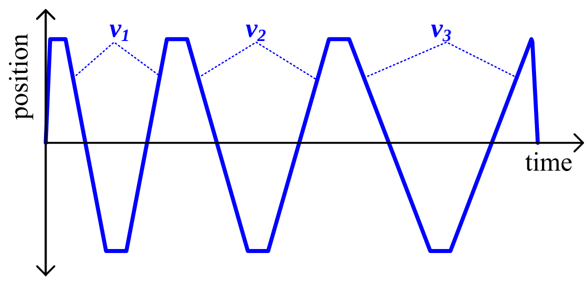

Figure 14. Overview of the calibration motion

3.2. Harmonic Extraction Algorithms

The data gathered from the scanner operation is then processed to extract the harmonic error (fingerprint). The data processing can be divided in three steps:

1. Time to spatial-domain conversion:
   The encoder readings are filtered with a sliding window. This process separates the actual movement at low frequency, from the fictitious movement of the harmonics at high frequency. The size of the sliding window provides the cut-off frequency of the filter.
2. Data "cleaning":
   The harmonics are separated from the microvibration disturbances. According to the motion profiles (see Section 3.1), the harmonics are located in the clean frequency region (2.5Hz-10Hz). This process extracts the harmonic data using the Fourier transform (FFT) to translate it into the frequency domain, and the inverse Fourier transform (iFFT) to

translate the filtered data back into the time domain [3].
3. Harmonic fingerprint estimation:
Once the data is "clean", this step reconstructs the harmonic error. Final estimation error (i.e. difference between harmonics and its estimation) is assessed in Section 4.

3.3. Harmonic Correction: In-Orbit/On-Ground

As explained in Section 2.2, there are two correction algorithms (see Fig 11), one in-orbit, to improve the actual pointing and the exported torques, and one on-ground, to improve the pointing knowledge.

The correction algorithm is basically the same for both in-orbit and on-ground. The harmonic error (fingerprint) is saved in a LUT (Look-up-Table), and is subtracted from the encoder raw measurement (see Fig. 15). Due to the significant variation of the harmonics (see Fig. 8), the LUT will cover the full angular range. In the case of in-orbit correction, as it is implemented on-board, the resources are limited. Each LUT is saved in 128kB, and the arithmetic is implemented in fixed-point. The on-ground correction, in contrast, has unlimited resources and the arithmetic can combine float and fixed-point.

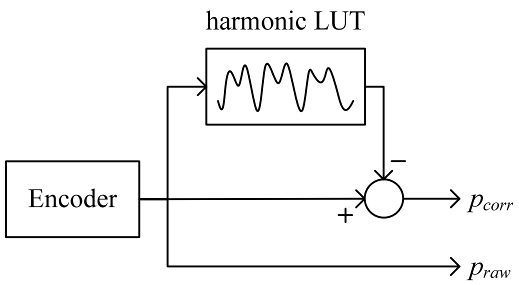

Figure 15. Harmonic correction

4. VALIDATION OF THE IN-ORBIT CALIBRATION

4.1. Assessment by Analysis

The effectiveness of the in-orbit calibration is assessed by analysis, in this section, and by test, in the next one. The analysis is based on a synthetic signal that simulates the motion profile and includes the effect of the microvibration environment and the mechanism dynamics. The harmonics are artificially added to the encoder signal, and the resulting signal is used for the harmonic extraction. Finally, the estimated harmonics are compared to the original ones to evaluate the estimation error.

Fig. 16 shows the results for one gimbal axis, the East-West (E/W), but the results are basically the same for both axes. The upper subplots show the real (in blue) and estimated (in green) harmonic content. Their difference, the estimation error, is shown in the lower subplots. The harmonics and errors are presented in the spatial domain on the left, and in the frequency domain on the right. The estimation error is below 0.04µrad except for the extremes of the angular range, where the estimation degrades (~0.22µrad). Fortunately, the operative range is within the region with low estimation error.

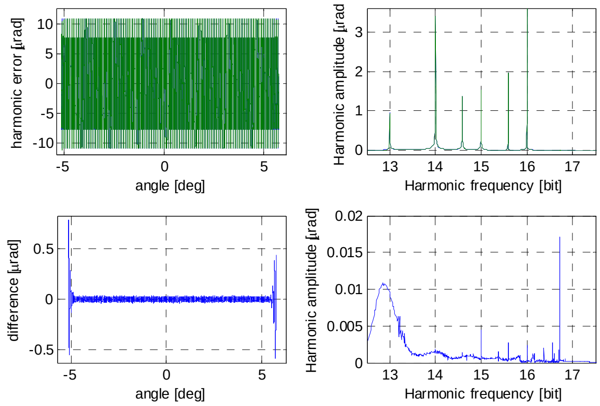

Figure 16. E/W-axis harmonic estimation and residuals

4.2. Tests results on SCA DM unit

The in-orbit calibration feasibility has been demonstrated in the Development Model (DM). The DM was initially developed for mechanical assessments, but its functionality was extended for this purpose. Nonetheless, the DM presented some limitations, and the in-orbit calibration was demonstrated only in the North-South (N/S) axis. At this point in time, the proof was sufficient to show the feasibility of the concept, but it will be complemented with more testing in next models.

The harmonic error (fingerprint) was extracted in three different ways: with interferometry (IFM), with free-oscillation movements (see Section 2.2) and with low speed profiles (i.e. the in-orbit calibration approach, see Section 3). The interferometry test set-up is shown in Fig. 17. The scanner is mounted on the microvibration facility to isolate it from external disturbances. A mirror is attached to the mirror dummy and three interferometers detect its orientation. The test consists in performing a quasi-static movement of the scanner and comparing the mirror orientation from the interferometers and the encoder readings. The difference between both signals is the harmonic error.

Fig. 18 shows the comparison of the three methods within the N/S angular window from 0.17º to 0.35º:

- "T05" and "T06" correspond to the interferometer measurements at two different constant E/W angles.
- "T11" and "T12" correspond to the free-oscillation movements at two different constant E/W angles.
- "T13+T14" corresponds to the constant low speed profiles, i.e. the in-orbit calibration.

The periods of the most relevant bits have been depicted by arrows in the upper subplot to illustrate the harmonic contribution. In this case BIT#14 is the major contribution. The harmonic frequency content is also depicted in the lower subplot.

The results show a good matching between the three methods, which validates the in-orbit calibration approach. The tests also demonstrated that there is no cross-coupling between axes. In particular, the N/S harmonics are not altered by the E/W angle. This is an essential assumption for the calibration.

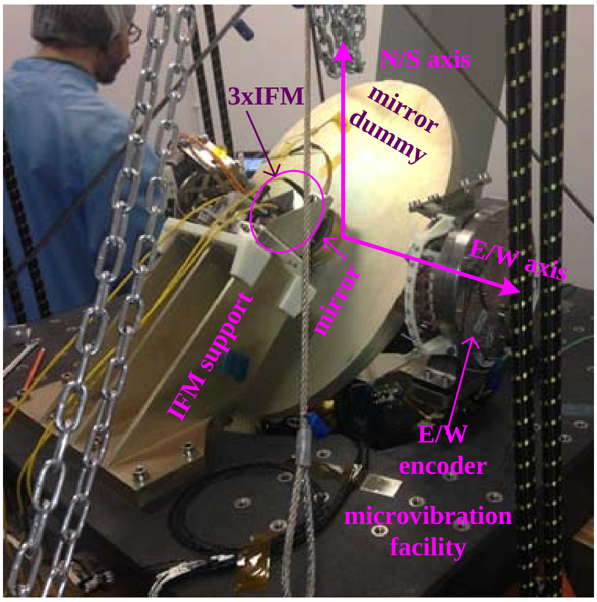

Figure 17. Test setup for interferometry tests: DM scanner on the microvibration facility and IFM support

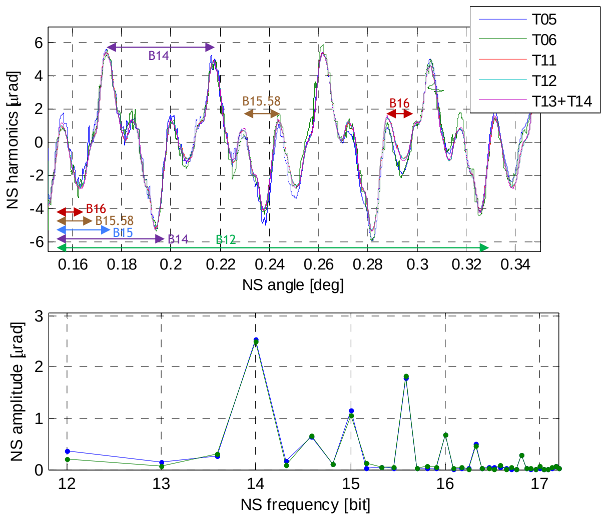

Figure 18. Comparison btw IFM and Free Oscillation Tests in the [0.15º, 0.35º] N/S window

An additional test was performed to validate the in-orbit correction concept (see Section 3.3). The harmonics were identified using the interferometer set-up within a N/S angular window from 0.1º to 0.3º. The test was repeated without and with correction, and the results are presented in Fig. 19. It can be seen that the correction provides a good suppression of the harmonics.

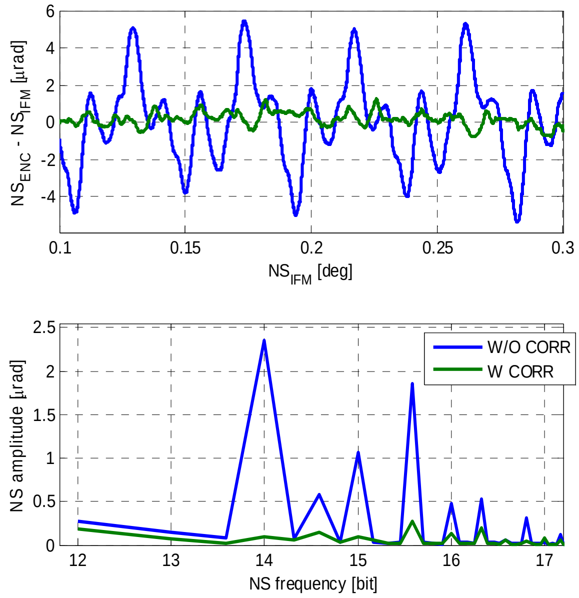

Figure 19. Harmonics with (w) and without (w/o) in-orbit correction

5. CONCLUSIONS

The 25-bit high precision encoder by CODECHAMP is a key element to reach the challenging requirements of the MTG scanner. However, the presence of the harmonic errors threaten the requirement fulfilment and thus, the mission performances. The SENER proposed solution is an in-orbit calibration that is repeated periodically (every 6 months as baseline). The solution includes three aspects: the scanner operation, the harmonic extraction algorithms and the harmonic correction. This proposal has been successfully validated both by analysis and by test.

6. REFERENCES

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