Instrumental Polarization of Antenna System for the SPOrt Experiment

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1 Introduction

The SPOrt (Sky Polarization ObseRvaTory) experiment has been selected by ESA for the Early opportunity phase onboard the International Space Station (ISS). It will consist of 4 polarimeters pointing the zenith from the ISS and operating in the 22-90 GHz range. A detailed description of the SPOrt experiment can be found elsewhere (see e.g. [1], [2]).
SPOrt scientific goals are:

1. the construction of polarized radiofrequency maps with 7° resolution for the study of the galactic emission, whose level ranges between hundreds and some μK from the lowest to the highest SPOrt frequency;
2. a possible detection of the polarized component of the Cosmic Background Radiation (CMB) which is expected at $\leq \mu K$ level.

The expected polarized signal from the sky (Galaxy + CMB) is few hundreds of μK at 20 GHz and of the order of a few μK at frequencies > 70 GHz. Unpolarized emission, instead, is about 3 K. Much care must be taken in the instrument design since the polarimeter must be able to separate polarized emission from this strong background of unpolarized radiation.
The antenna system of SPOrt radiometers is the leading part in producing spurious instrumental polarization. In fact lock-in system described in [3] is able to reject all the spurious correlated signal generated by the devices inside its ring [4]. The aim of this report is to analize the antenna system in order to identify the sources responsible for the spurious signals in Q and U radiometers output.
Section 2 gives a brief descrition of current baseline of SPOrt radiometers; Section 3 describes how instrumental polarization is created in the antenna system. Finally in section 4 we draw our conlcusions.

2 The SPOrt instrument

The radiometer configuration proposed for SPOrt can be divided in three parts (see figure 1): the antenna system, the low noise amplification section and the correlation unit.
In particular, the antenna system proposed for SPOrt consists of:

1. a corrugated horn that collects the incoming radiation and split it into its two linearly polarized components
$$\left\{ \begin{array}{l} E_x(\nu) \\ E_y(\nu) \end{array} \right. \tag{1}$$
2. an iris polarizer introducing a $\pi/2$ phase delay between the two linear components
$$\left\{ \begin{array}{l} A_C \propto E_x \\ A_L \propto E_y e^{j\frac{\pi}{2}} \end{array} \right. \tag{2}$$
where C and L denote the capacitive and inductive components of the polarizer respectively.
3. an orthomode transducer (OMT) that divides the two circular components. OMT reference frame is $\pi/4$ rotated with respect to the polarizer one. So, the components extracted by OMT are proportional to the following quantities:
$$\left\{ \begin{array}{l} A \propto \frac{1}{\sqrt{2}}\left(E_x + E_y e^{j\frac{\pi}{2}}\right) \\ B \propto \frac{1}{\sqrt{2}}\left(-E_x + E_y e^{j\frac{\pi}{2}}\right) \end{array} \right. \tag{3}$$

Correlation between the two circular components and integration provides the Stokes parameters Q and U. In fact, correlation unit performs real and imaginary parts of the complex product
$$AB^* = \frac{1}{2}\left[-\left|E_x\right|^2 + \left|E_y\right|^2 + j2\left|E_x\right|\left|E_y\right| cos\delta\right] \tag{4}$$
where δ is the phase difference between E_x and E_y. Integration provides
$$\begin{aligned} < A(t)\, B^*(t) > &\propto \left.\int A(\nu)\, B^*(\nu)\, e^{2\pi\nu\tau} d\nu\right|_{\tau=0} \\ &= \int A(\nu)\, B^*(\nu)\, d\nu \\ &= \int \left(-\left|E_x(\nu)\right|^2 + \left|E_y(\nu)\right|^2\right) d\nu + j2\int \left|E_x(\nu)\right|\left|E_y(\nu)\right| cos\delta d\nu \\ &\propto -Q + jU \end{aligned} \tag{5}$$
so that:
$$\left\{ \begin{array}{l} Q \propto Re\left(< AB^* >\right) \\ U \propto Im\left(< AB^* >\right) \end{array} \right. \tag{6}$$
These steps are true for an ideal instrument. In the following section we analize a real antenna system in order to estimate the contamination of Q and U outputs due to noise and unpolarized radiation.

3 Instrumental polarization

Since astrophysical emission is $10^{-4\div 6}$ polarized, non negligible contribution to spurious instrumental polarization comes only from unpolarized emission. In the following we will consider that sky signal collected by the horn is unpolarized. We assume matched devices.
The signals at the polarizer input (C and L modes) are:
$$\left\{ \begin{array}{l} A_{\|} = V_N^C + V_A^C \\ A_{\perp} = V_N^L + V_A^L \end{array} \right. \tag{7}$$

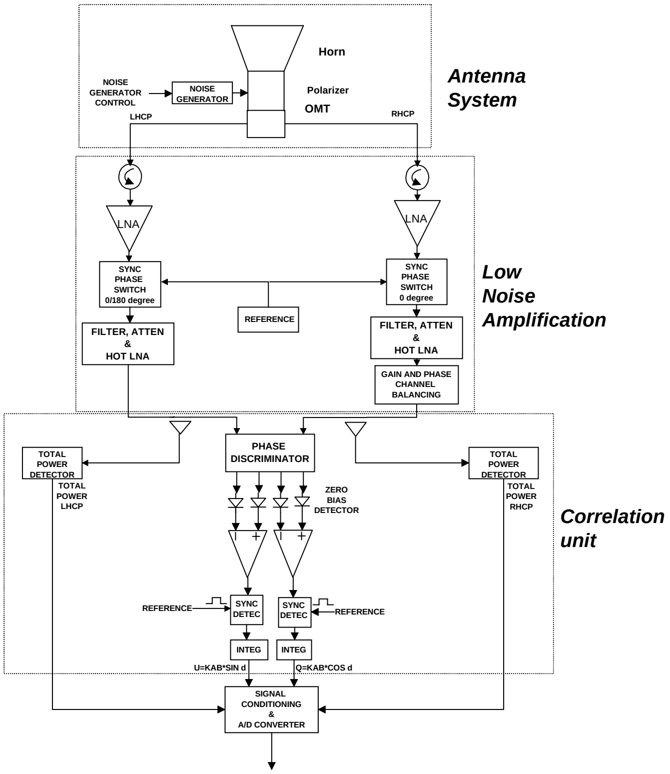

Figure 1: Current baseline of SPOrt radiometer. It consists of three parts: 1 - antenna system, 2 - amplification block and 3 - correlation unit.

where V_A^C and V_A^L are the two linear polarized components of the antenna signal at the horn output (capacitive and inductive components, i.e. they consist of the sky signal E_x and E_y plus the noise generated in the horn; spurious polarization generated in the horn can be considered negligible, see [5]) while V_N^C and V_N^L are the noise signals generated by the polarizer in the two linear propagation modes, recovered at polarizer input. At the output of the polarizer we have:

$$\left\{\begin{array}{l} A_C = S_C A_{\|} = S_C \left(V_N^C + V_A^C\right) \\ A_L = S_L A_{\perp} = S_L \left(V_N^L + V_A^L\right) \end{array}\right. \tag{8}$$

where S_C and S_L are the transmission parameters of the two principal linear polarizations of the polarizer. In ideal conditions $|S_C| = |S_L| = 1$, while $S_L/S_C = j$.
In the OMT reference basis the signals are:

$$\left\{\begin{array}{l} A_1 = \frac{1}{\sqrt{2}}\left[S_C\left(V_N^C + V_A^C\right) + S_L\left(V_N^L + V_A^L\right)\right] \\ A_2 = -\frac{1}{\sqrt{2}}\left[S_C\left(V_N^C + V_A^C\right) - S_L\left(V_N^L + V_A^L\right)\right] \end{array}\right. \tag{9}$$

Considering OMT as a 4 port linear network, the output signal can be written as a linear combination of the inputs:

$$\left\{\begin{array}{l} A = S_{A1}A_1 + S_{A2}A_2 \\ B = S_{B1}A_1 + S_{B2}A_2 \end{array}\right. \tag{10}$$

where S_{A1}, S_{A2}, S_{B1}, S_{B2} are the transmission parameters of the OMT that in ideal conditions match $|S_{A1}| = |S_{B2}| = 1$, $S_{A1}/S_{B2} = 1$ and $S_{A2} = S_{B1} = 0$.
From equations 9 and 10 we get

$$A = \frac{1}{\sqrt{2}}\left\{S_{A1}\left[S_C\left(V_N^C + V_A^C\right) + S_L\left(V_N^L + V_A^L\right)\right] - S_{A2}\left[S_C\left(V_N^C + V_A^C\right) - S_L\left(V_N^L + V_A^L\right)\right]\right\} \tag{11}$$

$$B = \frac{1}{\sqrt{2}}S_{B1}\left\{\left[S_C\left(V_N^C + V_A^C\right) + S_L\left(V_N^L + V_A^L\right)\right] - S_{B2}\left[S_C\left(V_N^C + V_A^C\right) - S_L\left(V_N^L + V_A^L\right)\right]\right\} \tag{12}$$

Grouping by $\left(V_N^C + V_A^C\right)$ and $\left(V_N^L + V_A^L\right)$:

$$A = \frac{1}{\sqrt{2}}\left[\left(S_{A1} - S_{A2}\right)S_C\left(V_N^C + V_A^C\right) - \left(S_{A1} + S_{A2}\right)S_L\left(V_N^L + V_A^L\right)\right] \tag{13}$$

$$B = \frac{1}{\sqrt{2}}\left[\left(S_{B1} - S_{B2}\right)S_C\left(V_N^C + V_A^C\right) - \left(S_{B1} + S_{B2}\right)S_L\left(V_N^L + V_A^L\right)\right] \tag{14}$$

In order to evaluate the spurious polarization, the time integration of the product AB^* is computed

$$\begin{aligned} < AB^* > \;&=\; \frac{1}{2}\Big\{\left(S_{A1} - S_{A2}\right)\left(S_{B1} - S_{B2}\right)^*\left|V_N^C\right|^2 + \left|V_A^C\right|^2\left|S_C\right|^2 \\ &\quad + \left(S_{A1} + S_{A2}\right)\left(S_{B1} + S_{B2}\right)^*\left|V_N^L\right|^2 + \left|V_A^L\right|^2\left|S_L\right|^2\Big\} \\ &=\; \frac{1}{2}\Big\{\left(S_{A1}S_{B1}^* + S_{A2}S_{B2}^*\right)\left|V_N^C\right|^2 + \left|V_A^C\right|^2\left|S_C\right|^2 \\ &\quad - \left(S_{A1}S_{B2}^* + S_{A2}S_{B1}^*\right)\left|V_N^C\right|^2 + \left|V_A^C\right|^2\left|S_C\right|^2 \\ &\quad + \left(S_{A1}S_{B1}^* + S_{A2}S_{B2}^*\right)\left|V_N^L\right|^2 + \left|V_A^L\right|^2\left|S_L\right|^2 \\ &\quad + \left(S_{A1}S_{B2}^* + S_{A2}S_{B1}^*\right)\left|V_N^L\right|^2 + \left|V_A^L\right|^2\left|S_L\right|^2\Big\} \end{aligned} \tag{15}$$

and we can write

$$\begin{aligned} < AB^* > \;=\; &\frac{1}{2}\Big\{\left(S_{A1}S_{B1}^* + S_{A2}S_{B2}^*\right)\left[\left|S_C\right|^2\left(\left|V_N^C\right|^2 + \left|V_A^C\right|^2\right) + \left|S_L\right|^2\left(\left|V_N^L\right|^2 + \left|V_A^L\right|^2\right)\right] \\ &+ \left(S_{A1}S_{B2}^* + S_{A2}S_{B1}^*\right)\left[\left|S_L\right|^2\left(\left|V_N^L\right|^2 + \left|V_A^L\right|^2\right) - \left|S_C\right|^2\left(\left|V_N^C\right|^2 + \left|V_A^C\right|^2\right)\right]\Big\} \end{aligned} \tag{16}$$

With respect to the equivalent temperatures (we neglect here the term $\Delta\nu k_B$), in matching conditions we can write:

$$\begin{aligned} |S_C|^2\left(\left|V_N^C\right|^2+\left|V_A^C\right|^2\right) &= |S_C|^2\left(T_{env}^{OMT+pol}\left(\frac{1}{|S_C|^2}-1\right)+T_A\right) \\ &= T_{env}^{OMT+pol}\left(1-|S_C|^2\right)+|S_C|^2 T_A \end{aligned} \tag{17}$$

where $T_{env}^{OMT+pol}$ is the OMT–polarizer environment temperature and T_A is the antenna temperature of the signal coming from the horn (sky signal + horn noise). The product becomes:

$$\begin{aligned} <AB^*> &= \frac{1}{2}\Big\{\left(S_{A1}S_{B1}^*+S_{A2}S_{B2}^*\right)\Big[T_{env}^{OMT+pol}\left(1-|S_C|^2\right) \\ &\quad +T_{env}^{OMT+pol}\left(1-|S_L|^2\right)+\left(|S_C|^2+|S_L|^2\right)T_A\Big] \qquad (18) \\ &\quad +\left(S_{A1}S_{B2}^*+S_{A2}S_{B1}^*\right)\left(|S_L|^2-|S_C|^2\right)\left(T_A-T_{env}^{OMT+pol}\right)\Big\} \qquad (19) \end{aligned}$$

Note that in the second term T_A and $T_{env}^{OMT+pol}$ have opposite sign. The spurious polarization of a not ideal antenna system is divided in two terms. The first one is due to the transmission parameters S_{B1} and S_{A2} of the OMT which describe the isolation between the two OMT channels; they are ideally zero, while in a real OMT they introduce correlation between the two channels. The second term is due to different attenuations of the two polarizer propagation modes; for an ideal polarizer $|S_L| = |S_C| = 1$, but for a real device $|S_L| \neq |S_C| < 1$ and their difference $|S_L|^2 - |S_C|^2$ produces a spurious polarization.

It is possible also to write the spurious polarization collecting the contributions with respect to T_A and $T_{env}^{OMT+pol}$

$$\begin{aligned} <AB^*> &= \frac{1}{2}\Big\{-T_A\Big[\left(S_{A1}S_{B1}^*+S_{A2}S_{B2}^*\right)\left(|S_C|^2+|S_L|^2\right) \\ &\quad +\left(S_{A1}S_{B2}^*+S_{A2}S_{B1}^*\right)\left(|S_C|^2-|S_L|^2\right)\Big] \\ &\quad +T_{env}^{OMT+pol}\Big[\left(S_{A1}S_{B1}^*+S_{A2}S_{B2}^*\right)\Big[\left(1-|S_C|^2\right)+\left(1-|S_L|^2\right)\Big] \\ &\quad +\left(S_{A1}S_{B2}^*+S_{A2}S_{B1}^*\right)\left(|S_C|^2-|S_L|^2\right)\Big]\Big\} \end{aligned} \tag{20}$$

and it is possible to write:

$$<AB^*> = N_{pol}T_{env}^{OMT+pol} - S_{pol}T_A \tag{21}$$

From [5] we get $|S_{B1}|^2 \sim |S_{A2}|^2 \sim -80$ dB, $|S_C|^2 \sim |S_L|^2 \sim -0.05$ dB and $|S_C|^2 - |S_L|^2 \sim -30$ dB. Thus the most important term of AB^* is:

$$\begin{aligned} <AB^*> &\sim \frac{1}{2}S_{A1}S_{B2}^*\left(|S_L|^2-|S_C|^2\right)\left(T_A-T_{env}^{OMT+pol}\right) \qquad (22) \\ &\sim 10^{-3}\left(T_A-T_{env}^{OMT+pol}\right) \end{aligned}$$

4 Conclusions

In the previous section we found that spurious polarization generated by antenna system depends on two leading terms. The first one is the isolation between the two channels of the OMT, while the second one is the difference between the insertion losses of the two principal linear polarizations of the polarizer.

Furthermore, instrumental polarized emission can be divided in two contributions which have different nature. $S_{pol}\,T_A$ represents the fraction of the signal coming from the horn which is correlated by the antenna system, while $N_{pol}\,T_{env}^{OMT+pol}$ is the polarized noise generated inside it. In the simple case where polarizer contamination is much greater than OMT contamination both are real numbers and the only contaminated output is Q.

The two coefficients, N_{pol} and S_{pol}, have opposite sign and depend on the same devices parameters. However, the two offsets depend also on two different environment parameters (OMT–polarizer environment temperature and antenna temperature of the signal from the horn).
For the current performances of the SPOrt experiment, $T_{env}^{OMT+pol} \sim 250$ K and T_A can be calculated as follows

$$T_A \sim T_{sky} + (A_h - 1)T_{env}^{horn}.$$

Assuming $T_{sky} = T_{CMB}$, $A_h \sim 0.1$ dB and T_{env}^{horn} we have

$$T_A \sim 10K << T_{env}^{OMT+pol}$$

From equation 22 the polarimeter offset of SPOrt radiometer is found to be $\sim 240mK$.

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