# EVN Doc. n.85 /1998

## Investigation on the Origin of the High Instrumental Polarization at the Medicina Telescope

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### 1. Introduction

In this note we investigate the possible reason of the large instrumental polarization at the Medicina telescope. In sect. 2 we analytically determine the D terms expected for a specific phase error occuring in the front-end section of one telescope. In sect. 3 we discuss the stations of Medicina and Effelsberg (previous 6 cm receiver) both having instrumental polarization of the type described in sect. 2. In sect. 4, by assuming that the similar error could be generated in the same element at both stations, we analyse the polarizers and the front-end waveguide sections. **We conclude that the phase error at Medicina very likely occurs in the directional coupler.** In fact, tests by Lochner (1997), at Effelsberg have indentified this element as the main responsible one for the high instrumental polarization. And the directional coupler at Medicina is a copy of that in Effelsberg (the two couplers have been made by using the same computer program with the same parameters.)

We therefore recommend to verify the possibility to produce a new directional coupler for Medicina as well.

### 2. Instrumental polarization due to a phase error

The incoming electric field E, with components $E_X$ and $E_Y$ along the two linear polarization axes, can be described by the two circularly polarized components $E_R$ and $E_L$, related to $E_X$ and $E_Y$ by:

$$E_R = 1/2(E_X + jE_Y) \tag{1}$$

$$E_L = 1/2(E_X - jE_Y)$$

Let us assume that at any point in the front-end from the feed to the polarizer a phase error is introduced such that the field component: $-jE_Y$ is phase shifted to become $-jE_Y e^{j\theta}$.

This implyes

$$E_{R_{output}} = 1/2[E_X + jE_Y e^{j\theta}]. \tag{2}$$

By rearranging:

$$E_{R_{output}} = 1/4[E_X + E_X + jE_Y(2e^{j\theta} + 1 - 1)]$$

$$= 1/4[E_X + jE_Y(1 + e^{j\theta}) + E_X - jE_Y(1 - e^{j\theta}) + E_X e^{j\theta} - E_X e^{j\theta}] =$$

$$= 1/4[(E_X - jE_Y)(1 - e^{j\theta}) + (E_X + jE_Y)(1 + e^{j\theta})] = 1/4(1 + e^{j\theta})[(E_X + jE_Y) + \frac{(1-e^{j\theta})}{(1+e^{j\theta})}(E_X - jE_Y)]$$

Therefore:

$$E_{R_{output}} = 1/4(1 + e^{j\theta})[E_R + \frac{(1 - e^{j\theta})}{(1 + e^{j\theta})}\ E_L] \tag{3}$$

The presence of the term $\theta$ produces an extra term in the right-circular polarized port which depends on the unwanted orthogonal mode $E_L$. The instrumental polarization, or $D_R$ term is the factor

$$D_R = \frac{(1 - e^{j\theta})}{(1 + e^{j\theta})} \tag{4}$$

If we repeat the analysis for $E_{L_{output}}$ we determine a $D_L$ identical to $D_R$.

For $|\theta| \ll 1$ $D_R \simeq -j(\frac{\theta}{2})$, the real part vanishes which implies a phase of $\pm 90$ degree for the D term: $D \simeq \frac{\theta}{2} e^{\pm j 90^\circ}$ in the complex notation.

**In conclusion, a phase error $\theta$ produces D terms $D \simeq \frac{\theta}{2} e^{\pm j 90^\circ}$**

## 3. Theory vs data

Roberts, Wardle and Brown (1994) noticed that the sum of the phases of the right and left D terms at Effelsberg and Medicina at 6 cm has almost been constant since many years around a value of 180 degrees (covering the period 1984-1991). Of course this only proves that the combination is constant over years and not that each phase is of 90 degree. However a recent observation (performed in 1995) analysed in Massi et al (1997) gives +84 degree for Medicina and -73 degrees for Effelsberg for the phase of the D terms of the LHC polarized feeds (the only one available). The error bars in the D term estimation depend on R-L instability during a run, imprecision in the position angle calibration and even on the software approximation used. Already the influence of the last factor is estimated to be around 10 degrees.

## 4. Station configuration

In sect. 3 we have discussed that the phase of the instrumental polarizations at Medicina and at Effelsberg are consistent with a value of $\pm 90$ degrees. As seen in sect. 2, such an error may be introduced by a phase error. In this section we try to see in which element of the front end such a phase error can be generated. We do that by comparing each element of the two telescopes, assuming for the moment that the similar error is generated in the same element at both station. We refer to the old receiver present in Effelsberg before 1997.

The Medicina polarizer (by Atlantic Microwave) covers the frequency range 4.4 - 5.2 GHz. Test points are separated by 200 MHz and the tested elipticity is about .4dB in the center of the band. Isolation is above 30 dB. The center of the band is lined up with the center of the VLBI frequency at 6 cm. As a comparison: The two Effelsberg polarizers (also from Atlantic Microwave) cover the band 4.6 to 5.1 GHz. Test points are spaced by 100 MHz. Ellipticity is .1 dB for one and .15 dB for the other polarizer in the central part of the band.

The polarizers have been extensively tested at the factory and the given performances are within the specifications. The reason of the high instrumental polarization (amplitude of the D terms for Medicina is about 17%) should therefore be searched for in some other element of the front-end.

There are two elements between the feed horn and the polarizer. The first one is the directional coupler to allow injection of the cal signal before the polarizer. The second one is the waveguide transition from circular to square waveguide. The very important point is that the directional coupler in Medicina (as well as the transition element ) has been build using the same computer program and the same parameters as used for the old front-end at Effelsberg (Tofani ,private communication ).

Since 1997 Effelsberg has a new configuration: a new chokeflange with integrated circular-square wavequide transition is mounted immediatly after the feed horn followed by a newly designed directional coupler with a square waveguide connected directly to a new polarizer AMC 0935 (Lochner, private communication; Mattes private communication). In the VLBI run of Februry 1997 the performance of the new set up in Effelsberg could be tested in terms of D terms. The previous value of $\simeq 8\%$ has now dropped to $\simeq 0.5\%$ (Massi and Aaron, 1997).

Is the new very good performance attributed to the new polarizer, to the new transition element, to the new coupler or to their combination?

Tests have been made at Effelsberg (Lochner, private communication) measuring the ellipticity of the old circular waveguide coupler plus new transition element and the new square waveguide directional coupler plus new transition element.

With the old coupler an ellipticity of 0.71 dB is measured in the center of the band 4.6 to 5.1.GHz. By applying the relationship between ellipticity ($\chi$) and D terms

$$D = (tan^{-1} 10^{\frac{\chi dB}{10}} - 45^{\circ})\ 100/57.296$$

a D term of 8% is found. That is exactly the value we measured reducing VLBI data.

With the new coupler the ellipticity drops to 0.14 dB which corresponds to $D = 1.6\%$.

A further improvement is introduced tuning the front-end for best ellipticity. The tuning produced an almost zero ellipticity as shown in Lochner's plots. This agrees very well with the low value of $D \simeq 0.5\%$ determined by Massi and Aaron (1997).

**In conclusion, at the Effelsberg telescope the previously high instrumental polarization depended on the old directional coupler.**

Therefore the main agent of the high instrumental polarization at the Medicina telescope is very likely to be the directional coupler as well, **since this elements is a copy of the old one at Effelsberg.**

## 5. Acknowledgments

We thank O. Lochner for reading and commenting the manuscript and H. Mattes, G. Tofani, J. Neidöfer, L. Moscadelli and S. Mariotti for helpful discussions. Maria Massi acknowledges support for her research by the European Union under contract FMGECT950012.

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## 6. *Appendix*

By private communication (Mariotti) we found that also the directional coupler at the telescope of Noto has been made by the same software used in Medicina. But the resulting amplitude of the instrumental polarization in Noto is only a few percent. Does that imply that the coupler is not the responsible for the high D terms at Medicina? In other words does this result contradict our previous analysis? We remind that the clear experimental fact we found is that since years the D terms at the two telescopes of Medicina and Effelsberg have phase of 90°. We have reproduced such D terms by a mathematical model shifting the phase of the linear field component $E_y$. **The point is whatever value the shift ($\theta$) of the linear component has, the unwanted circular component** (i.e. $E_L$ in eq. 3) **will be shifted by almost** 90° (phase of the D term). **The magnitude of the shift will determine only the percentage of the unwanted mode through the feed, that is the amplitude of the D terms**( i.e. $|D| = \theta/2$, see sect. 2). In fact also the amplitude of the D terms at Medicina and Effelsberg are different (17% for Medicina, which would correspond to a $\theta$ =0.17x57.29x2$\simeq$ 19°, and 8% for Effelsberg, corresponding to a $\theta = 9°$). And the cause of the 8% in Effelsberg was, as shown by Lochner, the coupler.

So, the fact that the amplitude in Noto is different from that for Medicina is not astonishing. The phase shift of the linear component for this telescope can be quite small. The D value of about 2% given in Massi et al (1997) it would correspond to a shift $\theta = 2°$. However, it would be interesting to check if the D terms of Noto have phase of 90° as well. Only this check can give experiment evidence for the same origin of error, like in Effelsberg and Medicina, but with smaller amplitude. Unfortunately little information is given in the literature for Noto at 6 cm. Massi et al (1997) found a strong dependence on frequency ( i.e. quite different values in the video converters) which makes impossible to determine a reliable averaged value. We conclude that the low amplitude of the instrumental polarization of Noto alone, does not contradict our analysis.