Basic Element for Square Kilometer Array Training (BEST): Evaluation of the Antenna Noise Temperature

P. Bolli[1], F. Perini[2], S. Montebugnoli[2], G. Pelosi[3], S. Poppi[1]

[1]Astronomical Observatory of Cagliari, National Institute for Astrophysics
Strada 54, Loc. Poggio dei Pini, 09012 Capoterra (CA), Italy
Tel: +39 070 711801; Fax: +39 070 71180222; E-mail: [pbolli, spoppi]@ca.astro.it

[2]Institute of Radio Astronomy, National Institute for Astrophysics
Via Fiorentina 3058/B, 40060 Villafontana (BO), Italy
Tel: +39 051 6965811; Fax: +39 051 6965810; E-mail: [f.perini, s.montebugnoli]@ira.inaf.it

[3]Department of Electronics and Telecommunications, University of Florence
Via C. Lombroso 6/17, 50134 Florence, Italy
Tel: +39 055 4796755; Fax: +39 055 4796767; E-mail: giuseppe.pelosi@unifi.it

Abstract

In this paper, a rigorous procedure for calculating the antenna noise temperature is described, and applied to the antenna BEST-1 (Basic Element for SKA Training – version 1), which represents one of the SKA (Square Kilometer Arr demonstrators. The SKA will be a new-generation radio telescope, with a collecting area 50 times larger than the area today's largest radio telescope. BEST is the Italian reduced-scale SKA demonstrator, based on the re-instrumentation about 8000 m² of the Northern Cross radio telescope, built with cylindrical parabolic antennas. In order to perform antenna-temperature analysis, an electromagnetic tool to accurately evaluate the antenna pattern in the whole sp surrounding the antenna itself is required. We used the commercial software *GRASP8*, developed by TICRA, to characte reflector antennas. The antenna temperature was evaluated using the guideline adopted by the Antenna Task Force of SKA world consortium. For BEST-1 at 408 MHz, we found an antenna temperature equal to 30 K in the zenith direction 60 K at the horizon. The numerical results have been verified through several celestial calibration radio sources.

Keywords: Radio astronomy; multireflector antennas; antenna temperature; antenna measurements; antenna radiation patterns; antenna arrays; antenna theory; Square Kilometer Array

1. Introduction

The Antennas Task Force (ATF), part of the Square Kilometer Array (SKA) International Engineering Working Group, has recently produced a white paper for the antenna subsystem [1]. This document will be considered by the SKA community, and by external engineering assessors charged with evaluating the SKA project. In that document, the performance of the four different antenna concepts still under consideration (small dishes with single-beam feeds, small dishes with phased-array feeds, aperture phased arrays, and the cylindrical reflector concept) were compared using their sensitivity figures, A_{eff}/T_{sys}, where A_{eff} is the effective area and T_{sys} is the system temperature.

The system temperature is defined as the sum of the receiver noise temperature and the antenna noise temperature. While the measurement of the receiver noise temperature is a quite common procedure, performed in the RF laboratory, the antenna tempera usually comes from a rough estimate performed through ra astronomical observations, or through local estimation of atmosphere's contributions. Obviously, this kind of evaluatio not appropriate for a consistent comparison among many diffe designs. To conform to a unique guideline for the calculation of antenna noise temperature, the Antennas Task Force decide adopt the procedure described in the technical memo by G. Co Medellin [2]. In that paper, a detailed description of several co butions to the brightness temperature distribution is given.

Moreover, a very accurate electromagnetic analysis of re tor antennas is required to evaluate the antenna pattern. Several ferent software packages, capable of characterizing the anten performance, could be used. Among these, the commercial ware package *GRASP8*, developed by TICRA, is one of the appropriate for reflector antennas.

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Finally, this procedure was applied to evaluating the antenna noise temperature of the Northern Cross re-instrumentation for SKA Training: BEST-1. The numerical results were compared with some experimental results obtained through astronomical observations. The procedure described here (see [3] for a complete description of that code) has general validity and, as such, is applicable to every kind of antenna.

This paper is organized as follows. The next section is devoted to describing the SKA project. Section 3 presents the BEST-1 antenna. In Section 4, the antenna-temperature formulation is discussed. Finally, in Section 5, the electromagnetic performance and the antenna temperature (both simulated and measured) are presented and discussed.

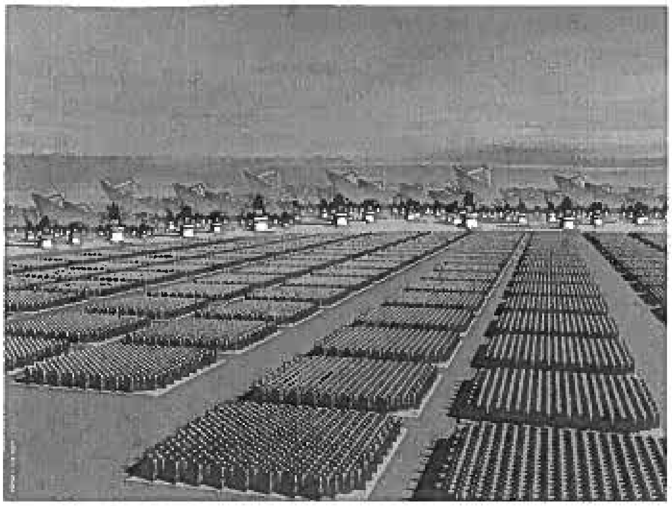

Figure 1a. An artist's sketch of the SKA "core" with aperture arrays and small dishes (from http://www.skatelescope.org).

2. The SKA Project

The SKA project (http://www.skatelescope.org/) represents the international challenge in the field of radio astronomy for the 21st century. It will be a radio telescope with an effective collecting area (one million square meters) more than 50 times greater than the largest telescope ever built (EVLA: Extended Very Large Array). The SKA will be an array with a maximum baseline among the antennas of 3000 km, and with 50% of the overall collecting area in a 5-km-diameter region, called the "core" (see Figure 1).

Given the large size of the project – both from the technological and financial points of view (the overall cost is estimated as one billion US dollars) – a worldwide consortium, composed of various institutions in the field of radio astronomy, was established. The aim of the consortium was to define the SKA specifications and requirements (the Scientific Working Group), and to drive its design (the Engineering Working Group). Due to the very wide frequency range (100 MHz to 25 GHz), a hybrid concept, with more than one sensor, will probably be used. To provide such a collecting area and frequency coverage at an acceptable cost, all the institutions participating in the SKA are designing and building prototype systems, antennas, and sensors.

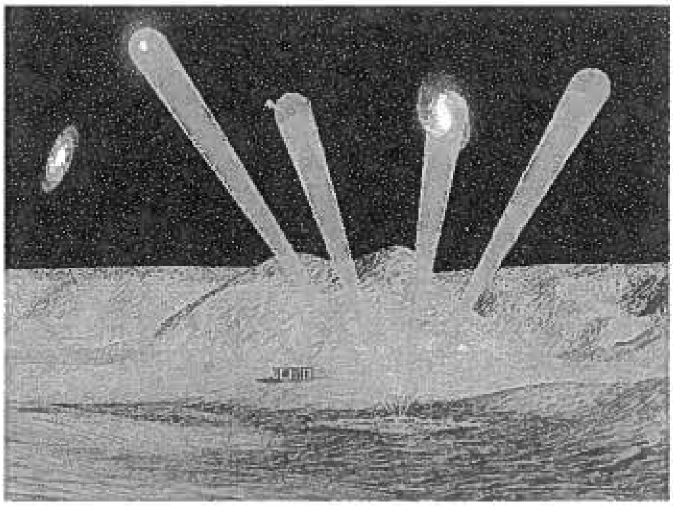

Figure 1b. An artist's sketch of SKA beamforming (from http://www.skatelescope.org).

As far as the European participation, inside the EU 6th Frame Program, a four-year (mid-2005 to mid-2009) project, called SKADS (SKA Design Study) was funded with about 10,000,000 €. The SKADS consortium includes 30 participants from several European countries, and from Australia, South Africa, and Canada. The Italian contribution to this project, funded with about 1,000,000 €, is based on a re-instrumentation of part of the Northern Cross radio telescope, a large low-frequency array based on cylindrical-reflector antennas. The BEST project is fully described in the next section.

3. Basic Element for SKA Training

The Northern Cross radio telescope (see Figure 2), located in Medicina (Bologna, Italy), is an antenna array based on two series of antennas: one lying in the east/west (E/W) direction, and the other following a north/south (N/S) line. The E/W arm is a unique cylindrical-reflector antenna, 564 m long and 35 m wide. The N/S arm is based on 64 identical antennas, each having a parabolic-cylindrical profile, with a length of 23.5 m and a width of 7.5 m (see Figure 3a).

Figure 2. An aerial view of the Northern Cross radio telescope.

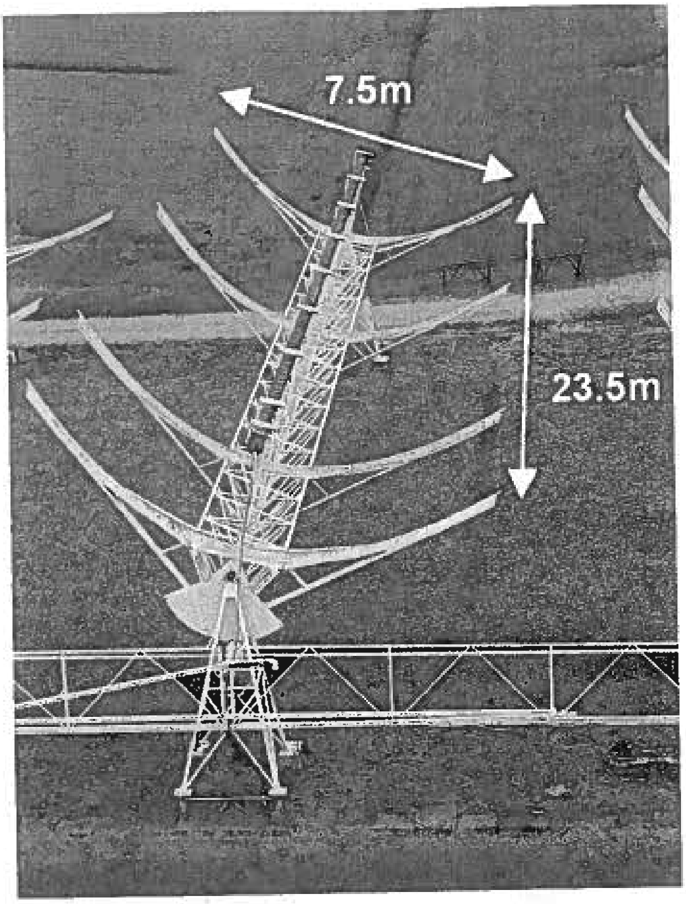

Figure 3a. The N/S arm single cylinder (BEST-1).

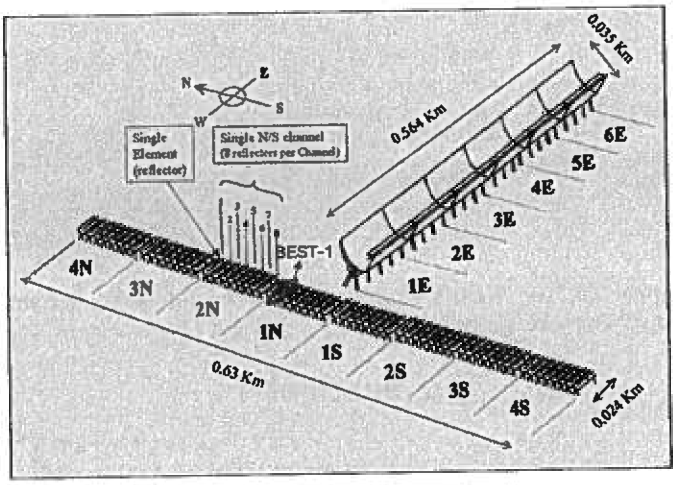

Figure 3b. BEST-1 in the Northern Cross radio telescope.

The BEST-1 test bed – the first one of the three planned and funded by the SKADS program – is based on a single N/S reflector element, as shown in Figure 3. BEST-1 was completed during September 2004. Information about BEST-1 can be found in [4, 5], as well as on the Web: http://www.ira.inaf.it/%7Eskawork. Each element of the N/S arm has a reflecting surface made of 430 parallel steel wires (0.5 mm diameter), located about 2 cm apart. The feed is placed in the focal line and consists of 64 $\lambda/2$ dipoles, allowing a bandwidth of about 16 MHz at 408 MHz ($\lambda = 0.735$ m). In order to efficiently illuminate the main reflector with the dipoles, a flat subreflector mirror (23.5 m × 0.374 m) was placed behind the focal line. The antenna reflects a single linear polarization, that for which the electric field of the incident wave is parallel to the wires. Four receivers, one every 16 dipoles, were installed on the focal line. The collecting area is 176 m^2, for an effective area of about 125 m^2.

The amplified RF signals are sent via analog optical fiber links to the receiver room, located inside the central building, where they are converted to the intermediate frequency (30 MHz). The signals are then cascaded with an analog phase shifter (digital phase shifters and beamforming are planned to be used in the future), and added together to form the total beam pattern. The direction of the main beam in the sky is in the following ranges: co-elevation, $-45° \le \Theta_0 \le 45°$ with respect to the zenith direction (mechanical pointing), and right ascension, $-3.45° \le \alpha \le 3.45°$ with respect to the local meridian (electrical pointing).

In the second and third planned steps of the project (BEST-2 and BEST-3), many other receivers will be installed on the focal lines of the Northern Cross radio telescope, including also in the E/W arm. BEST-2 will be ready in mid-2007, and will be equipped with eight N/S cylindrical reflectors with four receivers each, for a total of 32 new receivers installed. The total collection area will be 1410 m^2. Finally, BEST-3 is planned to be completed in the summer of 2008. At this stage, 56 receivers will be installed on 14 N/S antennas, and 24 receivers will be installed on six E/W focal-line segments. The total collecting area will become about 7260 m^2, the same area as a 96-m-diameter parabolic dish.

4. Antenna Temperature Theory

The evaluation of the antenna temperature requires the knowledge of both the antenna's power pattern (P_n) and the brightness-temperature distribution (T_b) in the whole space surrounding the antenna itself. According to [2, 6], a very general formula for defining the antenna noise temperature at the frequency ν is given by

$$T_{ant}(\nu;\Theta_0,\Phi_0,\Delta_0) = \frac{\iint\limits_{\substack{\theta=0,\pi \\ \phi=0,2\pi}} P_n(\nu;\theta,\phi) T_b(\nu;\theta',\phi') \sin\theta d\theta d\phi}{\iint\limits_{\substack{\theta=0,\pi \\ \phi=0,2\pi}} P_n(\nu;\theta,\phi) \sin\theta d\theta d\phi} \quad (1)$$

where the integration variables, θ and ϕ represent the spherical coordinates in the reference system of the antenna's pointing direction, and θ' and ϕ' are the coordinates in the reference system, with z' along the zenith direction. Moreover, $(\Theta_0,\Phi_0,\Delta_0)$ are the antenna pointing directions (co-elevation angle, azimuth angle, and angle of rotation of the antenna system around its main axis, respectively), as explained in [6] and sketched in Figure 4.

By using the following formula, it is possible to find θ',ϕ' for every θ,ϕ, given the position of the antenna's axis in terms of $(\Theta_0,\Phi_0,\Delta_0)$ [6]:

$$\theta' = \arccos\left[\sin\Theta_0 \sin\theta \sin(\phi+\Delta_0) + \cos\Theta_0 \cos\theta\right],$$
$$\phi' = \arctan\left[\frac{A+B-C}{D-E+F}\right], \quad (2)$$

$$A \equiv \sin\Phi_0 \sin\theta \sin(\phi + \Delta_0),$$

$$B \equiv \cos\Phi_0 \cos\Theta_0 \sin\theta \sin(\phi + \Delta_0),$$

$$C \equiv \cos\Phi_0 \sin\Theta_0 \cos\theta,$$

$$D \equiv \cos\Phi_0 \sin\theta \cos(\phi + \Delta_0),$$

$$E \equiv \sin\Phi_0 \cos\Theta_0 \sin\theta \sin(\phi + \Delta_0),$$

$$F \equiv \sin\Phi_0 \sin\Theta_0 \cos\theta.$$

It is worth noticing that since the brightness-temperature distribution could be assumed to be rotationally invariant, $T_b(\nu;\theta')$ can be used instead of $T_b(\nu;\theta',\phi')$. In Equation (1), the brightness-temperature distribution of the entire scene can be subdivided in two main contributions: one from the sky (range $0° \le \theta' \le 90°$) and the other from the ground (range $90° < \theta' \le 180°$). The first term is the radiation coming directly from the sky ($T_b^{sky}(\nu;\theta')$), whereas the latter is due to both the sky radiation reflected from the ground and the emission from the ground itself (usually, $T_{gnd} = 300\,\mathrm{K}$).

The expression for the sky brightness-temperature distribution is [2, 7]

$$T_b^{sky}(\nu;\theta') = T_{bo}(\nu)e^{-\tau_{\nu,\theta'}(0,h_a)} + \int_0^{h_a} \frac{k_a(\nu;z')T_{atm}(z')e^{-\tau_{\nu,\theta'}(0,z')}}{\sqrt{1-\left\{\sin(\theta')/\left[1+(z'/r_e)\right]\right\}^2}}dz' \tag{3}$$

where r_e is the Earth's radius; $T_{bo}(\nu)$ is the background brightness temperature due to cosmic emission; $T_{atm}(z')$ and $k_a(\nu;z')$ are, respectively, the physical temperature and the absorption coefficient of the atmosphere at the specified height above ground, z'; and

$$\tau_{\nu,\theta'}(0,h_a) = \int_0^{h_a} \frac{k_a(\nu;z')}{\sqrt{1-\left\{\sin(\theta')/\left[1+(z'/r_e)\right]\right\}^2}}dz' \tag{4}$$

is the zenith opacity. For the absorption coefficient, the water-vapor and oxygen absorption-coefficient models were adopted as proposed in [2]. Moreover, for the background cosmic-emission term, the expression $T_{bo}(\nu) = T_{CMB} + T_{g_o}(\nu_0/\nu)^{\beta}$ was used, where T_{CMB} is the cosmic microwave background emission (equal to 2.73 K), and the second term is the galactic emission, which depends on frequency and on the observed direction in the sky. Finally, T_{g_o} is the base temperature, β is the spectral index, and ν_0 is a frequency-normalization factor. The sky-brightness temperature as a function of frequency was calculated at different zenith angles with an average cosmic emission (as proposed in [2]) of $\beta = 2.75$, $T_{g_o} = 20\,\mathrm{K}$, $\nu_0 = 408\,\mathrm{MHz}$ and $h_a = 100\,\mathrm{km}$. As Figure 5 shows, the sky-brightness temperature is dominated at low frequencies by the cosmic emission. At higher frequencies, $T_b^{sky}(\nu;\theta')$ depends mainly on the opacity of the atmosphere.

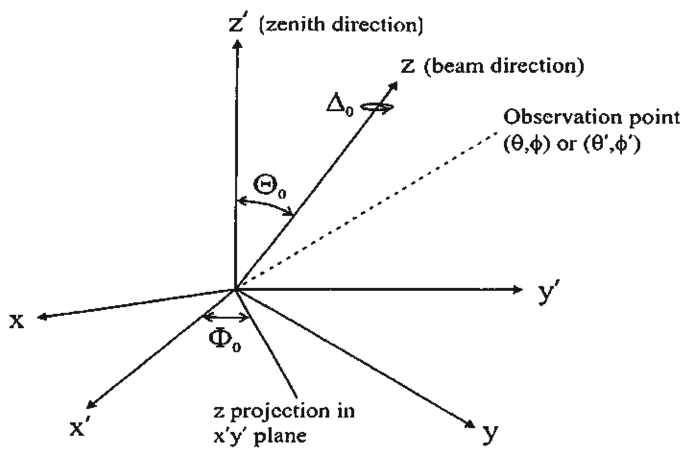

Figure 4. A representation of the coordinate systems.

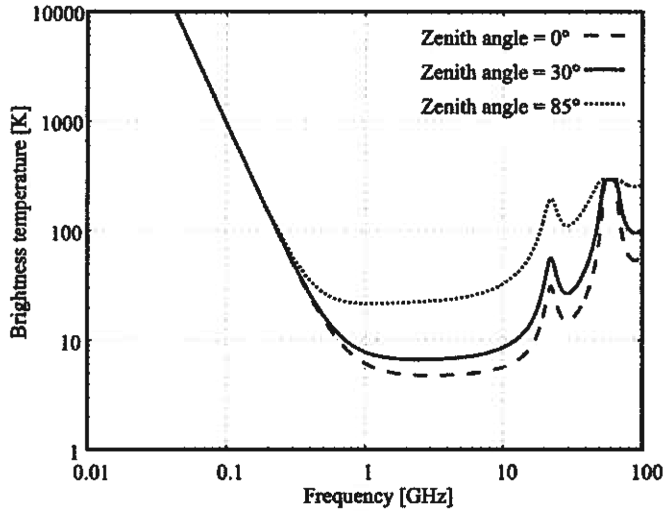

Figure 5. The sky brightness temperature as a function of frequency.

As described in [2], both the ground emission and the ground scattering are polarization-dependent processes. Therefore, the integrand in the numerator of Equation (1) needs to be expressed in terms of the components along the directions relative to the plane of incidence. Hence, the argument of the integral in Equation (1) may be rewritten as

$$P_n(\cdot)T_b(\cdot) = \begin{cases} T_b^{sky}(\cdot)P_n(\cdot), & 0° \le \theta' \le 90° \\ T_{b\|}(\cdot)P_{\|}(\cdot) + T_{b\perp}(\cdot)P_{\perp}(\cdot), & 90° < \theta' \le 180° \end{cases} \tag{5}$$

where $T_{b\|}(\cdot)$ and $T_{b\perp}(\cdot)$ are the contributions to the brightness temperature from the scattered component of the sky emission plus the emission from the ground in its appropriate polarization components. $P_{\|}(\cdot)$ and $P_{\perp}(\cdot)$ are, respectively, the horizontal and vertical power-pattern components in the incident plane of the ground-air interface. A very detailed description of these terms was reported in [2].

5. Numerical Results and Measurements

In order to evaluate the antenna temperature of BEST-1, an electromagnetic analysis of this system was performed through the commercial software *GRASP8*, developed by TICRA (www.ticra.com). *GRASP8* is a very powerful and versatile tool for simulating and designing reflector antennas. It is based on classical high-frequency techniques: Geometrical Optics and Physical Optics (PO) [8]. The aim of the electromagnetic analysis proposed here was to evaluate the antenna pattern at 408 MHz in the whole space surrounding the structure. The physical antenna model used in *GRASP8* to characterize BEST-1 was composed of two wire-grid mirrors: a cylindrical-parabolic reflector, and a rectangular plane as a secondary reflector. Several approximations were used in the model. One of them was to assume that the antenna operates in free space, with no coupling interaction with the other nearby antennas and with no ground effects taken into account. Moreover, 64 ideal half-wavelength dipoles with identical phase and amplitude were used to illuminate the reflector.

The electromagnetic analysis was performed by using the PO analysis, which replaces each mirror with an appropriate set of induced currents. The far field was then computed by numerically integrating the currents over all the reflector's surface. The results obtained with *GRASP8* were compared with those reported in [9], which were based on the solution of the Pocklington equation through a bi-dimensional Method of Moments calculation. Our results were in a good agreement with those in [9].

As known, reflector antennas with a rectangular rim are characterized by different patterns in the E plane and H plane. Hence, the patterns need to be evaluated in several azimuthal cuts. Moreover, since the integral that allows us to evaluate the antenna temperature extends to the whole sphere surrounding the antenna – even in the backlobe direction – a wide-angle analysis pattern was necessary. In Figure 6, two bi-dimensional grids of the antenna's pattern in the elevation-over-azimuth plane are plotted in a small range of angles near the main beam. In detail, the electric-field amplitudes (expressed on a logarithmic scale) are reported for the co-polar component (Figure 6a) and for the cross-polar component (Figure 6b). The two components were necessary to implement Equation (5). As expected, the rectangular shape of the aperture resulted in a fan elliptical beam, with the main axis in the H plane and the minor axis in the E plane.

The calculated antenna temperatures for different pointing zenith angles of BEST-1 are shown in Figure 7. Notwithstanding the fact that the maximum antenna co-elevation is 45°, the numerical analysis was expanded up to 80° to give a more general view of the antenna-temperature behavior. In detail, ten different points were considered between zenith, $\Theta_0 = 0°$, and the quasi-horizon, $\Theta_0 = 80°$. The three curves are related to the contributions coming from the ground ($\theta' > 90°$, dashed curve), and from the sky ($\theta' \leq 90°$, solid curve). Finally, the dash-dot line shows the total antenna temperature, which is the sum of the previous two contributions.

The contribution from the sky is almost constant at any pointing direction, depending basically on what the antenna's main beam gets through (at 408 MHz, the sky brightness temperature does not fluctuate very much with the zenith angle: it is 23.8 K at the zenith direction and 28.5 K at the 80° co-elevation angle). As far as the ground contribution is concerned, the temperature increases when the antenna goes down, because, according to

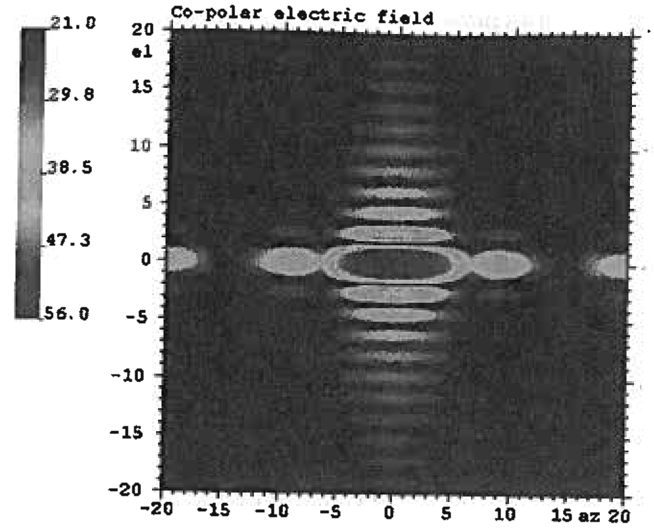

Figure 6a. The BEST-1 bi-dimensional main beam in the elevation-over-azimuth plane for the co-polar component.

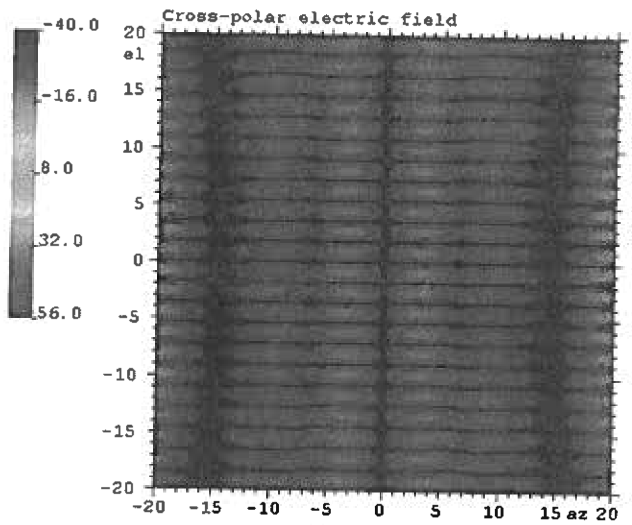

Figure 6b. The BEST-1 bi-dimensional main beam in the elevation-over-azimuth plane for the cross-polar component.

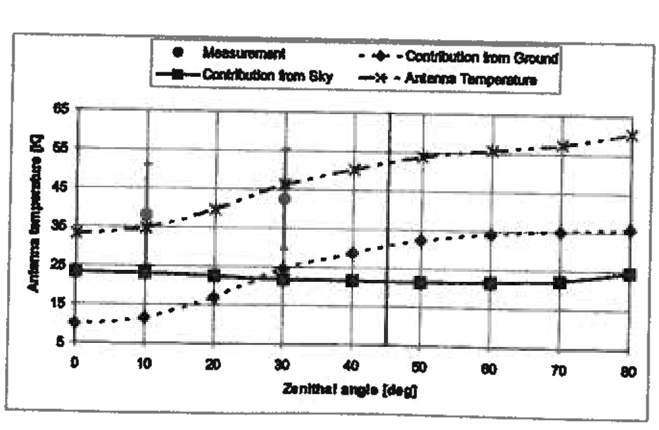

Figure 7. The antenna temperature contributions as a function of zenith angle.

expectations, higher sidelobes now point to the hot ground (300 K).

In order to verify these numerical results, some experimental measurements were performed. The system noise temperature of BEST-1 was measured by detected transits of some "calibrators" (i.e., strong radio sources with well-known and well-established emitted power-flux densities). Actually, the measurements allowed us to get the A_{eff}/T_{sys} figure. Hence, in order to determine T_{sys}, the effective area was evaluated as the product of the geometrical area and the antenna's efficiency. This last parameter was determined through the *GRASP8* numerical analysis (the value turned out to be about 71% [3]), and not directly from measurement. However, we have verified this simulated value with an independent numerical analysis, performed through a completely different methodology based on the Method of Moments and described in [9]. We then estimated the antenna temperature from the system noise temperature using $T_{sys} = T_{ant} + T_{rec}$, where T_{rec} is the noise temperature of the receiver connected to the dipoles. For the previous formula, we measured a noise temperature equal to 47 K, a value that also included the loss introduced by the transmission lines between the dipoles and the low-noise amplifiers. The calibrators employed for the measurements were Cassiopeia-A,

$$\left(\alpha = 23^h\ 23^m\ 24^s, \delta = 58°\ 48'\ 54''\right),$$

and Virgo-A,

$$\left(\alpha = 12^h\ 30^m\ 49^s, \delta = 12°\ 23'\ 28''\right),$$

whose transits, for the latitude (+44° 31' 13.8") of Medicina, happened, respectively, at about 10° and 30° of zenith angle. The measurements, reported with grey circles and vertical bars in Figure 7, agreed very well with the numerical results, showing good accuracy in the proposed procedure. The measurement uncertainties depended on those of the calibrator fluxes, which were given within ±10% to ±15%.

6. Acknowledgment

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Introducing the Feature Article Authors

Pietro Bolli was born in Arezzo, Italy, in 1973. He received the Laurea degree in Electronic Engineering and the PhD degree in Computer Science and Telecommunications from the University of Florence in 1999 and 2003, respectively.

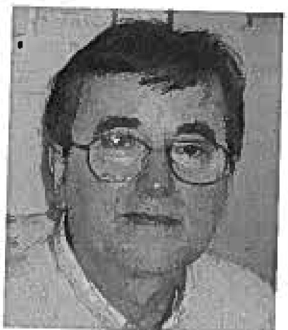
In 1999, he worked under a research grant at the Arcetri Astrophysical Observatory. In 2001, he was a Visiting Fellow at the National Astronomy and Ionosphere Center, Cornell University, Ithaca, NY. From 2002 to 2005, he was a Research Engineer at the Institute of Radioastronomy, Bologna.

He is currently at Cagliari Astronomical Observatory, where he conducts research on electromagnetic aspects of instrumentation for radio astronomy applications, and in particular for the new Italian project, the Sardinia Radio Telescope. His current research interests encompass electromagnetic analysis of large reflector antennas and passive microwave devices, with particular emphasis on electromagnetic coupling among circular horns in feed-array systems.

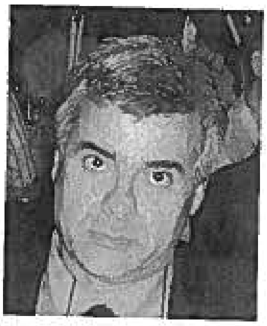
Since 2005, he has been the Secretary of the Committee on Radio Astronomy Frequencies, which coordinates activities at the European level to keep the frequency bands used by radio astronomers free from interference. In 2006, P. Bolli received the Giorgio Barzilai Prize for the best young scientist paper at the Italian National Congress on Electromagnetics (XVI RiNEm).

Federico Perini was born in Bologna, Italy, in 1974. He received the Laurea degree in Telecommunications Engineering (summa cum laude) from the University of Bologna in 2001. His thesis was on the applicability in the field of radio astronomy of analog fiber-optic links. In particular, this was applied to the two antennas of the Medicina radio-astronomical station of the Institute of Radio Astronomy (IRA) of INAF: the 32 m VLBI dish and the large low-frequency array called Northern Cross.

Since 2002, he has worked at the Medicina station as an RF project engineer. In particular, he designed the new low-noise amplifier of the Northern Cross radio telescope. He has been involved in the design of the new analog receiver chains for this array: from the modifications of the focal lines up to the input of the digital receivers. Since 2006, he has been involved in the SKADS (SKA Design Study), a four-year international program funded by the EU. The aim of this research program is to develop new technologies, components, architectures, and software algorithms applicable to the Square Kilometer Array: the next-generation radio telescope. His activity is take care of developing the analog receiver chain of the Italian SKA demonstrator (BEST), based on the re-instrumentation of part of the Northern Cross radio telescope. He is also involved in the design of the receiver of the European SKA demonstrator (EMBRACE).



Stelio Montebugnoli is a senior engineer in charge of the Medicina radio-astronomical station of the Institute of Radio-astronomy of INAF in Bologna. He is in charge of the technological development of the large Northern Cross radio telescope, the biggest T-shaped antenna in the northern hemisphere (30000 m^2 of geometrical collecting area). In 1994, he designed a real-time FFT-based high-time and high-frequency-resolution spectrometer, which allowed the detection of the water-line emission on the Comet SL-9 E fragment impact zone in the Jupiter high atmosphere. This unique water-line detection represented a breakthrough for the international bio-astronomy community. In 2001, he led a detection experiment on a medium-size NEO (near-Earth obiter) (1998WT24) at a distance of about 2,000,000 km from the Earth (illuminated by the Goldstobne CA, USA, NASA dish), using the same back-end connected to the Medicina 32 m VLBI dish. Presently, is the engineer in charge of the Italian team within the SKA consortium in Europe (SKADS).

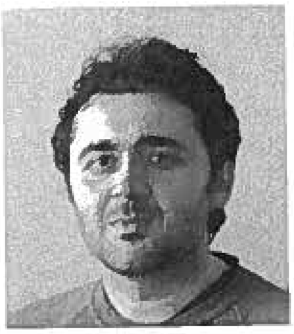


Giuseppe Pelosi was born in Pisa, Italy, on December 25, 1952. He received the Laurea (Doctor) degree in Physics (summa cum laude) from the University of Florence in 1976. Since 1979, he has been with the Department of Electronics and Telecommunications of the same university, where he is currently Professor of Electromagnetic Fields. Prof. Pelosi was a Visiting Scientist at McGill University, Montreal, Quebec (Canada) from 1993 to 1995, and Professor at the University of Nice-Sophie Antipolis (France) in 2001.

Prof. Pelosi is mainly involved in research in the field of numerical and asymptotic techniques for electromagnetic engineering, with particular interest in antennas, circuits, microwave and millimeter-wave devices, and scattering problems. He is also very active in the uncovering of electromagnetic-engineering and telecommunications history.

He is coauthor of over 300 scientific publications on the aforementioned topics, appearing in international refereed journals and at national/international conferences. He has been guest Editor of several special issues of international journals. He is also coauthor of three books: *Finite Elements for Wave Electromagnetics* (with P. P. Silvester, IEEE Press, 1994), *Finite Element Software for Microwave Engineering* (with T. Itoh and P. P. Silvester, Wiley, 1996), and *Quick Finite Elements for Electromagnetic Fields* (with R. Coccioli and S. Selleri, Artech House, 1998).

Prof. Pelosi is a Fellow of the IEEE. He has been member of the Board of Directors of the Applied Computational Electromagnetics Society (ACES) (1999-2001), of the Board of Directors of the IEEE Central and South Italy Section (1992-1995 and 1995-1998), and Chair of the IEEE Magnetics Chapter of the same Section (1996-1999).



Sergio Poppi was born in 1972 in Argenta, Italy. In 1998, he obtained a Laurea degree in Astronomy from the Bologna University, with a thesis in the field of astrochemistry. In 1999, he obtained a fellowship grant for studying HII regions by means of radio recombination lines at the TeSRE/CNR Institute in Bologna.

From 2002 to 2005, he was at the Istituto di Radioastronomia (INAF) in Bologna, in the framework of the Sky Polarization Observatory. There, he was involved in the characterization of a 32 GHz receiver, optimized for polarization measurements. In 2005, he collaborated with the DEIS (Department of Electronics, Computer Science, University of Bologna, Italy), for a project about indoor localization. He is presently at the Cagliari Astronomical Observatory (INAF), in the framework of the Sardinia Radio Telescope (SRT). His current research fields comprise metrology, high-precision pointing for radio telescopes, and software development.