Sergei Gulyaev et al.: Characterization and Calibration of the 12-m Antenna in Warkworth, New Zealand, IVS 2010 General Meeting Proceedings, p.113–117
http://ivscc.gsfc.nasa.gov/publications/gm2010/gulyaev.pdf

# Characterization and Calibration of the 12-m Antenna in Warkworth, New Zealand

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## Abstract

The New Zealand 12-m antenna is scheduled to start participating in regular IVS VLBI sessions from the middle of 2010. Characterization procedures and results of calibration of the New Zealand 12-m radio telescope are presented, including the main reflector surface accuracy measurement, pointing model creation, and the system equivalent flux density (SEFD) determination in both S and X bands. Important issues of network connectivity, co-located geodetic systems, and the use of the antenna in education are also discussed.

## 1. Antenna Location

The New Zealand 12-m VLBI radio telescope is located some 60 km north of the city of Auckland, near the township of Warkworth. A preliminary survey has been conducted to find the precise coordinates of the invariant point of the antenna (the intersection of the azimuth and elevation axes). They are [1]:

$$\text{Latitude} = 36^\circ\ 26'\ 05.3375''\,\text{S}$$
$$\text{Longitude} = 174^\circ\ 39'\ 47.6988''\,\text{E}$$

or using geocentric coordinates:

$$\begin{aligned} X &= -5115327.28\,\text{m} \\ Y &= \phantom{-}477844.04\,\text{m} \\ Z &= -3767196.04\,\text{m}. \end{aligned}$$

The coordinates are given in terms of ITRF2000 at the epoch of the survey (March 2010). The survey was conducted in close collaboration with the New Zealand Geological and Nuclear Science Research Institute (GNS Science) and the Land Information New Zealand (LINZ). Real-time kinematic GPS was used in order to survey several points on the rim of the main reflector for the series of positions in azimuth and elevation. Coordinates were calculated with respect to GPS station “WARK” — one of the “PositioNZ” network stations established in November 2008 at the radio telescope site. The accuracy of the axes intersection point, with respect to WARK is estimated to be within 0.1 m.

New Zealand’s traditional role in contributing to the global reference frame determination is through its GNSS “PositioNZ” network operated by LINZ in a partnership with GNS Science. The PositioNZ network [2] consists of thirty-three GNSS continuously operating reference stations (CORS) in mainland New Zealand, plus one station on Chatham Island (400 km east of

Christchurch) and three in Antarctica. Data from several of these sites are forwarded to the International GNSS Service (IGS) where they are incorporated into solutions used to determine GNSS satellite orbit and global reference frame determinations. The GNSS station at the radio telescope site (WARK) is one of them.

The accuracy of the radio telescope invariant point coordinates will be subsequently refined with the use of a variety of survey techniques. With this purpose, four geodetic monuments have been built in the vicinity of the antenna (15–20 m from its pedestal).

## 2. Technical Characteristics, Equipment and Network Connectivity

The 12-m antenna was manufactured by Patriot Antenna Systems Inc. in Albion, Michigan, USA. The antenna specifications are provided in [3].

The radio telescope is equipped with a coaxial dual band (S and X) dual polarization (circular left/right) feed horn, which was specifically developed by Patriot Antennas. An S/X receiver has been constructed with the help of Peter McCulloch and the University of Tasmania. A Symmetricom Active Hydrogen Maser MHM-2010 (75001-114) with 5MHz, 10MHz, 100MHz, 1pps (pulse per second) outputs and a 1pps sync facility is installed. A digital base band converter (DBBC) developed at the Italian Institute of Radio Astronomy is expected to be installed in May 2010. The AUT VLBI receiving system uses a Mark 5B+ data recorder developed at MIT Haystack Observatory.

Both S and X receivers have been installed and preliminary figures for SEFD are around 4000 Jy, a figure that is higher than expected. Investigations in collaboration with the manufacturer are underway and several areas in which improvements can be made have been identified.

With wide-spread development of e-VLBI, the issue of broadband network connectivity becomes essential for both existing and emerging radio astronomical facilities. Internationally, New Zealand's major broadband supplier is Southern Cross Cables Ltd — a commercial organization, which owns and operates the cable connecting New Zealand with Australia in the West and with the US in the North-East direction. This is a multi-wavelength cable with the capacity of up to 2 Tbps. Locally, the regional advanced network operating in New Zealand is KAREN (Kiwi Advanced Research and Education Network), which provides a 10 Gbps connectivity between New Zealand's educational and research institutions. The establishment of a KAREN GigaPoP at the 12-m radio telescope site in Warkworth is currently in progress.

## 3. Surface Accuracy

Photogrammetric measurements of the antenna surface were performed by Kevin Sinclair and Bob Cato from Patriot Antenna Systems (Cobham SATCOM). Figure 1 shows contours for the deviation of the real surface from the theoretical (shaped) surface. The absolute values of deviation reach a maximum of 0.5 mm, with an $rms = 0.4$ mm, which is somewhat higher than the expected $rms$ according to the manufacturer's initial specification of $0.012'' = 0.3$ mm. No noticeable change in $rms$ with the elevation angle was detected. Holographic measurements of the dish are planned in the near future.

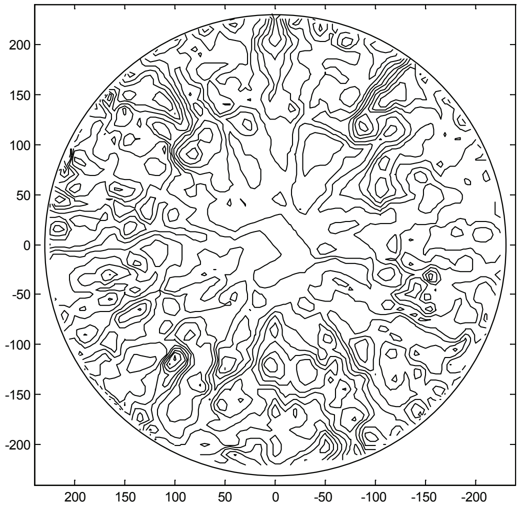

Figure 1. Contour map showing the deviation of the measured main reflector surface from the theoretical one. Ten contours are used in the range from −0.5 to 0.5 mm. X and Y axes are in inches.

## 4. Pointing Map

The AUT radio telescope has an azimuth-elevation mount. For engineering reasons, there always exists a difference $dA$ and $dE$ between the desired and actual azimuth, $A$, and elevation, $E$, positions. The aim of the pointing map is the minimization of the errors $dA$ and $dE$ for the observable hemisphere. The true angle for the horizontal component of this mis-pointing is the so-called cross-elevation $dXE = dA \cos E$. The telescope control system is capable of pointing corrections, which are calculated by the control system as follows

$$dXE = \theta_1 + \theta_2 \cos E + \theta_3 \sin E + \theta_4 \sin E \cos A + \theta_5 \sin E \sin A \tag{1}$$

$$dE = -\theta_4 \sin A + \theta_5 \cos A + \theta_7 + \theta_8 \cos E + \theta_9 \cot E \tag{2}$$

Here the nine regressed coefficients, $\theta_1$ to $\theta_9$, used in (1) and (2), correspond to different physical offsets and errors in the vertical (elevation) and horizontal (cross-elevation) positions as described in Table 1.

Note that $\theta_4$ and $\theta_5$ coefficients are used in both $dXE$ and $dE$ expressions. The parameter $\theta_6$ is not used in this approximation, but is retained to correct for gravitational bending proportional to $\sin E$ in possible future applications.

Mathematically, the problem of finding nine coefficients from nine or more observations can be solved using the method of least squares. In this case the regression problem is linear, despite the duplication of the parameters. The MATLAB code given in Listing 1 provides the solution in terms of pointing coefficients and the *rms* for both $dXE$ and $dE$. Note that the algorithm concatenates the two Vandemonde matrices associated with equations (1) and (2), but never forms the possibly ill-conditioned normal equations in order to solve for the unknown parameters.

Table 1. The physical interpretation and subsequently regressed values of the parameters used in Equations (1) and (2).

| | *Description* | *value* |
|---|---|---|
| $\theta_1$ | Azimuth collimation error | 0.1218 |
| $\theta_2$ | Azimuth encoder offset | −0.4861 |
| $\theta_3$ | Elevation axis skew angle | −0.0576 |
| $\theta_4$ | Inclination of the azimuth axis in the N-S direction | 0.1266 |
| $\theta_5$ | Inclination of the azimuth axis in the E-W direction | −0.0254 |
| $\theta_6$ | Not used in this model | — |
| $\theta_7$ | Elevation encoder offset | 0.5119 |
| $\theta_8$ | Gravitational deformation of radio telescope | 0.0586 |
| $\theta_9$ | Residual refraction coefficient | −0.0173 |

Listing 1. MATLAB code for fitting parameters to (1) and (2).

```
% Define the models to be fitted
dXE = @(p,A,E) p(1) + p(2)*cos(E) + p(3)*sin(E) + p(4)*sin(E).*cos(A) + ...
     p(5)*sin(E).*sin(A); % Eqn. (1)
dE = @(p,A,E) -p(4)*sin(A) + p(5)*cos(A) + p(6) + p(7)*cos(E)+p(8)*cot(E);
     % Eqn. (2) with numbering change

% Data Input
B = xlsread('D:\data.xls'); % read Excel file with observational data
A = B(:,1); % Column 1: Azimuth in rad
E = B(:,2); % Column 2: Elevation in rad
dAz = B(:,3); % Column 3: measured error in cross-elevation in degrees
dEl = B(:,4); % Column 4: measured error in elevation in degrees

% Set up the Data matrix
N = length(dAz); % # of observations
y = [dAz; dEl];
Va = [ones(N,1), cos(E), sin(E), sin(E).*cos(A), sin(E).*sin(A), zeros(N,3)];
Vb = zeros(N,8);
Vb(:,[4:8]) = [-sin(A), cos(A), ones(N,1), cos(E), cot(E)];
V = [Va; Vb];

% Pointing map correction coefficients -- same units as dAz and dEl (deg).
pfit = V\y % Do the Least-squares fit

dAfit_error = norm(dXE(pfit,A,E) - dAz)/sqrt(N) % Compare fits
dEfit_error = norm(dE(pfit,A,E) - dEl)/sqrt(N) % RMS, 1 sigma
```

Several bright and compact radio sources were observed both in S and X bands in both polarizations (RCP and LCP). With the Matlab code from Listing 1, we processed the observational data, which consisted of 19 measured positions on the sky in S-band and 25 positions in X-band. As the result, the regressed pointing coefficients were determined for the X-band (Table 1).

The error (*rms*) of this solution is pretty small: 0.03° for both azimuth and elevation. No detectable offsets between the X-band RCP and X-band LCP were found. However, we detected a noticeable elevation offset (squint) of the S-band beams relative to the X-band beam position. The measured elevation offsets are:

(S-band RCP) − (X-band) = −0.15° and (S-band LCP) − (X-band) = 0.07° .

## 5. Conclusion

The IVS VLBI2010 Progress Report [4] outlines a number of strategies to improve the long-term accuracy of geodetic VLBI with an eye to achieving 1-mm long-term accuracy on baselines. Among these strategies are: “to increase the number of antennas and improve their geographic distribution” and “to increase the number of observations per unit of time”. These IVS strategies can best be addressed through construction of new small ($\sim$ 12 m), fast-slewing automated antennas in areas that are under-represented (Southern Hemisphere) or lack (e.g., New Zealand) geodetic VLBI stations. Developing this approach, AUT University has invested US$1m in a geodetic VLBI system, consisting of a fast-slewing automated 12-m antenna, hydrogen maser clock, digital receiving and digital backend systems, and a 1 Gbps network connectivity.

In November 2008, a new GNSS station (WARK) was built at the AUT radio telescope site. It is part of the New Zealand GNSS network “PositioNZ”. An accurate tie is established between the radio telescope antenna and GNSS station.

The New Zealand 12-m antenna is scheduled to start participating in regular IVS VLBI sessions in the middle of 2010.

Being a research tool for astronomy and geodesy, the antenna will be used in a new educational program in astronomy which was started in 2009 at AUT’s School of Computing and Mathematical Sciences — an Astronomy Major in the framework of the Bachelor of Mathematical Sciences degree. It is envisaged that both undergraduate and postgraduate students will use the radio telescope in their research projects and as a teaching resource in the courses taught at AUT such as Astrophysics, Radio Astronomy, Practical Astrophysics, Space Geodesy, and others.

## 6. Acknowledgements

We are grateful to Lewis Woodburn (AUT), Peter McCulloch (University of Tasmania), Mark Godwin, Peter Shield, Kevin Sinclair and Bob Cato from Cobham SATCOM (Patriot Antenna Systems), Neville Palmer and John Beavan from GNS Science, as well as David Collett and Graeme Blick from LINZ.

## References

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