Conical Spiral Antennas for EoR applications

A. Jiwani, S. K. Padhi, M. W. Waterson, Peter J. Hall, A. Sutinjo and J. G. bij de Vaate*

ICRAR/Curtin University, Australia
* ASTRON, The Netherlands

EoR Global Signal workshop, November 19-21, Sydney
Outline

• Square Kilometre Array (SKA) context

• Conical wire spiral antenna
  - Single polarization

• Performance of antenna
  - Return loss
  - Gain, radiation patterns etc.
  - Can we make a dual-polarization spiral?

• Conical antenna on real soil
  - Do we need a ground plane?

• EoR antenna design
  - Conical spiral and meander spiral antenna

• Conclusions
  - Including key questions for any high-gain SKA realization
Introduction

• The Square Kilometre Array (SKA) will be the world’s biggest radio telescope

• Two SKA core sites: Western Australia (low-band) and South Africa (mid-band)

• SKA-low will
  - Operate between 70 – 450 MHz, and consist of sparse aperture phased arrays
  - Have several million active antenna elements, with “Phase 1” having ~200,000 antennas (2016-2020)
  - Be an “ICT telescope” giving >>10x the sensitivity, field-of-view, and survey speed of existing instruments
  - Build on pathfinder experience (LOFAR, Murchison Wide field Array, ...)
  - Likely deliver transformational science in the study of the Early Universe
Motivation for considering spirals

- Higher gain $\rightarrow$ fewer elements and receiver chains $\rightarrow$ lower SKA cost

- Conical spiral antennas are true frequency independent antennas
  - Cover the required 6.5 : 1 frequency range
  - Relatively constant beam characteristics (beamwidth, polarization, ...)
  - Usefully wide beamwidth while maintaining other desirable properties
  - High F/B ratio for most of the band
    - Possibly omit costly ground plane
  - Low ellipticity (axial ratio)
  - Good polarization purity (wide band)
  - Consistent terminal impedance
    - Benign active element
    - Consistent radiation patterns
  - Low mutual coupling in array

- Note: just making a wideband element may not be sufficient
  - SKA-low may need 2 bands on array sparseness and calibration grounds

*Can we do better than dipole-derivatives currently used in LOFAR, MWA, ..... ?*
Conical log spiral basics

- Classic work by Dyson in late 1950s

- Cones previously used in radio astronomy
  - e.g. Clark Lake Array 15 to 125 MHz
  - Before the era of modern e.m. modelling

- Other applications: e.g. military radar

Designed using three angular parameters
- Half cone angle: $\theta_0$
- Wrap angle: $\alpha$
- Strip width: $\delta$

- Travelling wave antenna

- Balanced feed
  - We use 2-arm spirals (easy broadband balun)
Spiral antenna experiments at ICRAR

Single-polarized sheet

Dual-polarized conical spiral prototype

Interspersed conical spiral array

Full-size SKA-low prototypes

Sheet and wire conical spiral models

Dual-polarized wire conical spiral prototype
Conical wire log spiral

- Conical spiral with constant arms widths
  - Easier to prototype
  - More manufacturable?

- Retains many desirable sheet spiral characteristics

- Feed impedance changes as a function of arm widths

- LMR-400 coax; $\alpha = 75^\circ$ ; $\theta_0 = 15^\circ$
Return loss and gain: wire spiral

Simulation results (free space)

- Return loss is below 10 dB in the 70 – 450 MHz band
- Gain is above 4 dBi over the whole band
- Cross polarisation is better than -10 dB above 100 MHz.
Radiation pattern: wire spiral

Simulation results

- Smooth patterns
- Backlobes < -10 dB
Measurements of wire spiral

- Constructed a 6.5 : 1 frequency range, 1/3 scale prototype (210 – 1350 MHz)

- Measurements show good overall agreement with simulation
  - (within a basic measurement environment)

Calculated and measured radiation pattern of 1/3 scale wire spiral at 700 MHz.
Dual-polarized wire spiral antenna

- SKA-low requires two opposite polarizations
- Wire spirals are inherently single polarized
- We could intersperse LH and RH spirals in array, but
  - More cost
  - Increases minimum packing distance → unacceptable
- Can we make a “counter-wound” dual-polarized antenna?
  - Two oppositely-polarized spirals overlaid
Dual wire spiral characteristics

Simulation results

- Return loss is below -10 dB over the 70 – 350 MHz bandwidth
- Poor isolation between the two antennas → high cross polarization
Dual wire spiral: can it ever work?

1-turn RHCP spiral with a LHCP field incident

Isolation for two values of $\theta_0$ with $\alpha = 75^\circ$

- Higher isolation with low $\theta_0$.
- Reduce apex radius to match length of one turn with wavelength at 450 MHz which further improves isolation.
- However, this increases the height of the dual spiral to > 16 m !!!
Soil dielectric measurement

- Measured relative permittivity of 5 soil samples (courtesy CSIRO)
- Permittivity measurements with different moisture contents
- Fitting with dispersive model (Debye 2 parameter model)
Do we need a ground plane?

Sensitivity of isolated sheet spiral at SKA site – infinite extent back surfaces

- Spiral with a metallic ground plane has higher sensitivity than SKA-low goal
- Spiral over the soil does not meet goal below 110 MHz, but is close enough to warrant detailed performance and cost trade-off
- Highly-directive SKA-low antennas (like the conical spiral) may not need a metallic ground plane
  - Or use only very wide mesh
EoR spiral antenna:

Meander conical spiral antenna

Conical spiral antenna

Gain (dBi)

EOR spiral
Meander-line spiral

Return loss (dB)

EOR spiral
Meander-line spiral

Freq (MHz)

Freq (MHz)
Conclusions

- Spirals are true frequency-independent antennas, making them worth considering for contemporary radio astronomy, including SKA-low
  - Benign terminal impedance behaviour and low mutual coupling are particularly attractive properties in a sparse, active array

- Interspersed L/R spiral arrays are relatively expensive and give unacceptably wide minimum spacing in SKA-low

- Counter-wound spirals do not perform well, given practical dimensions
  - Spirals are not likely to be attractive as SKA-low antennas

- Spiral antenna performance is insensitive to soil parameters
  - (As with most upward-pointing directive antennas)
  - No, or rudimentary, ground planes may be OK

- A spin-off of the ICRAR SKA-low work is a large conical spiral for a radiometer searching for the all-sky “epoch of re-ionization” spectral signature

- EM analysis and synthesis techniques can lead to better performing and characterized spirals