Conical Spiral Antennas for EoR applications

International Centre for Radio Astronomy Research

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

Curtin University

The University of Western Australia

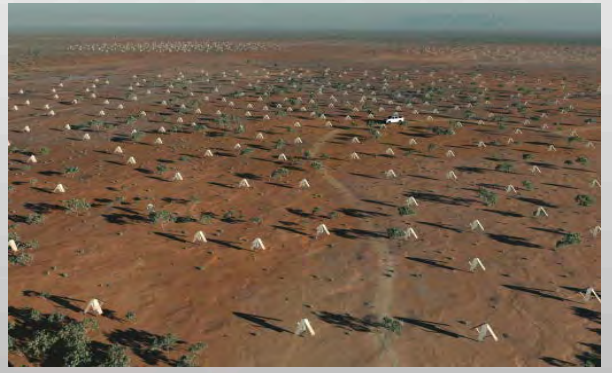
Outline

- 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

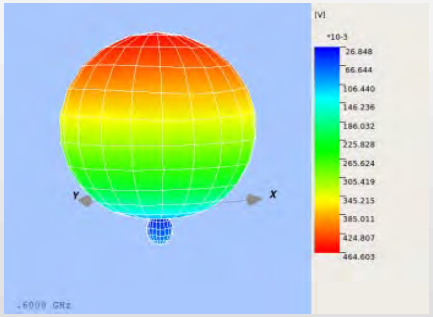


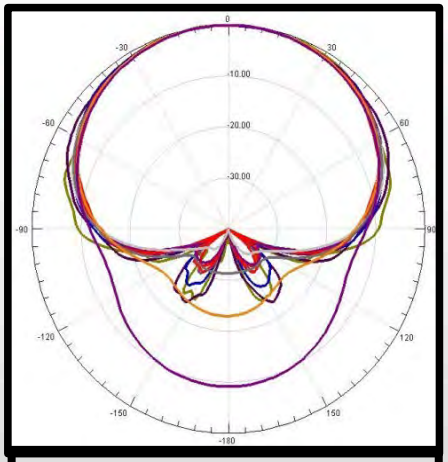


Motivation for considering spirals

- Higher gain → fewer elements and receiver chains → 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



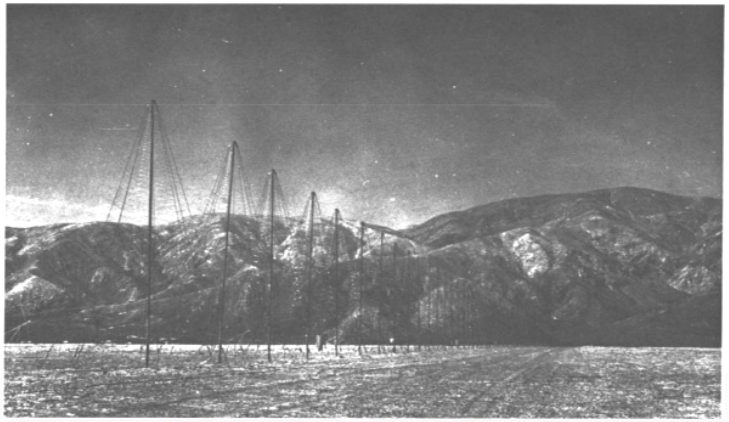


6.5 : 1 spiral

- 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, ... ?

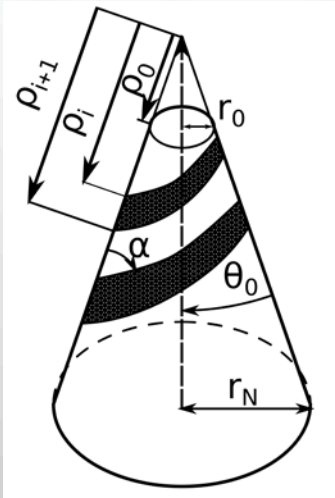
Conical log spiral basics

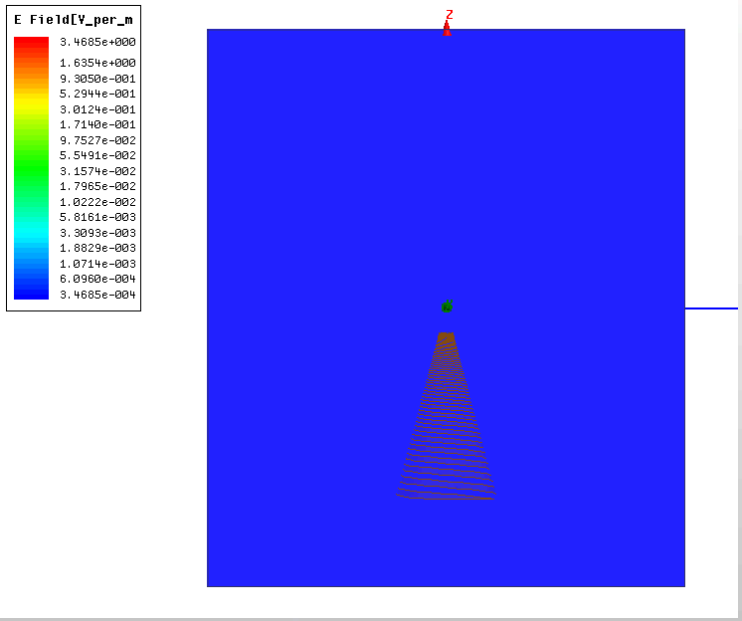


- Classic work by Dyson in late 1950s
- Cones previously used in radio astronomy
  - e.g. Clark Lake Array 15 to 125 MHz
  - Before the era of modern e.m. modelling
- Other applications: e.g. military radar

Designed using three angular parameters

- Half cone angle: θ_0
- Wrap angle: α
- Strip width: δ

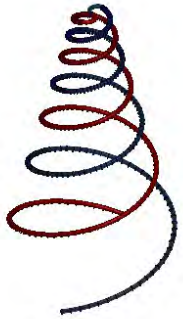




- Travelling wave antenna
- Balanced feed
  - We use 2-arm spirals (easy broadband balun)

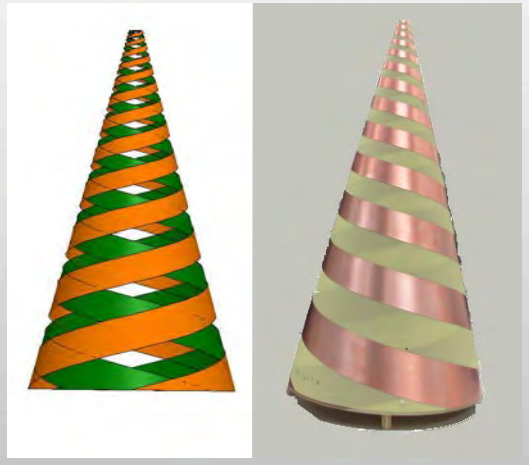
Spiral antenna experiments at ICRAR

Single-polarized sheet

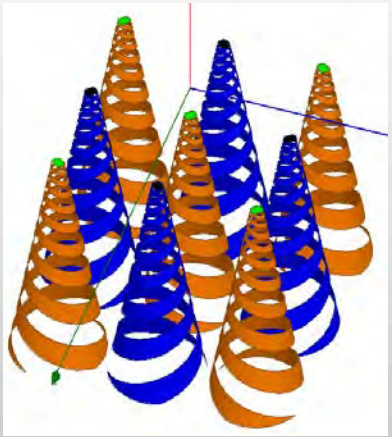


Sheet and wire conical spiral models

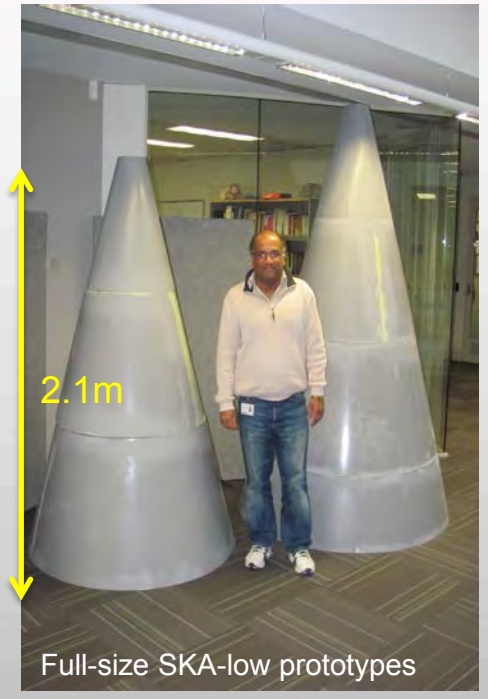
Dual-polarized wire conical spiral prototype



Dual-polarized conical spiral prototype



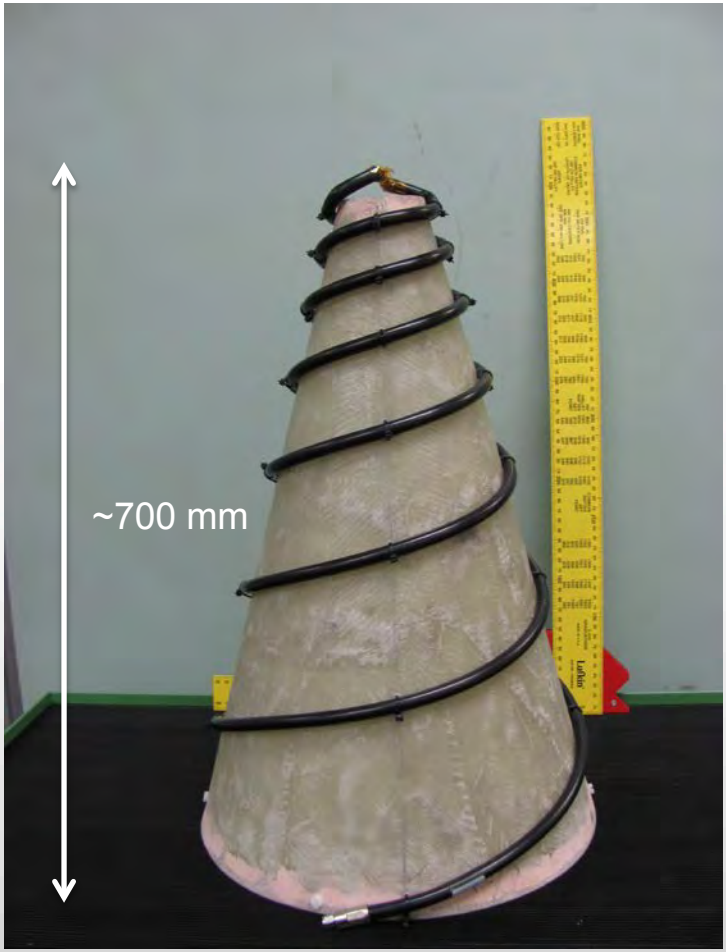
Interspersed conical spiral array



Full-size SKA-low prototypes

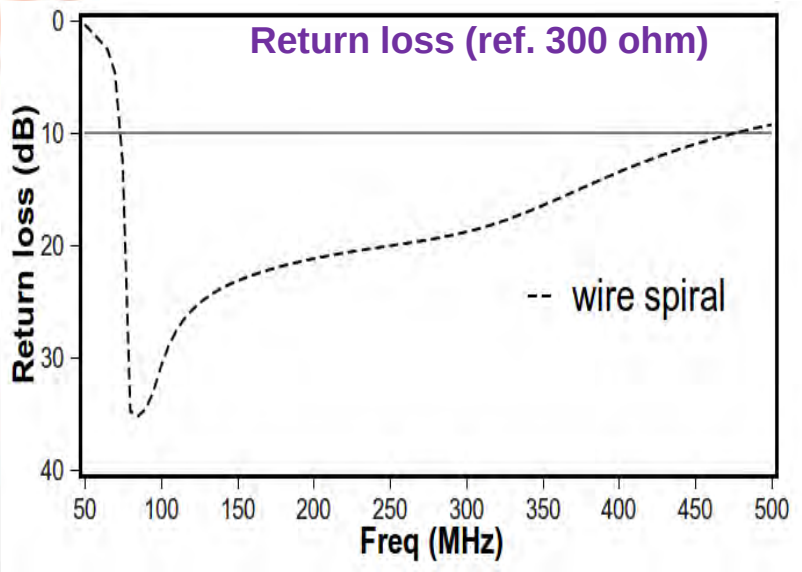
Conical wire log spiral

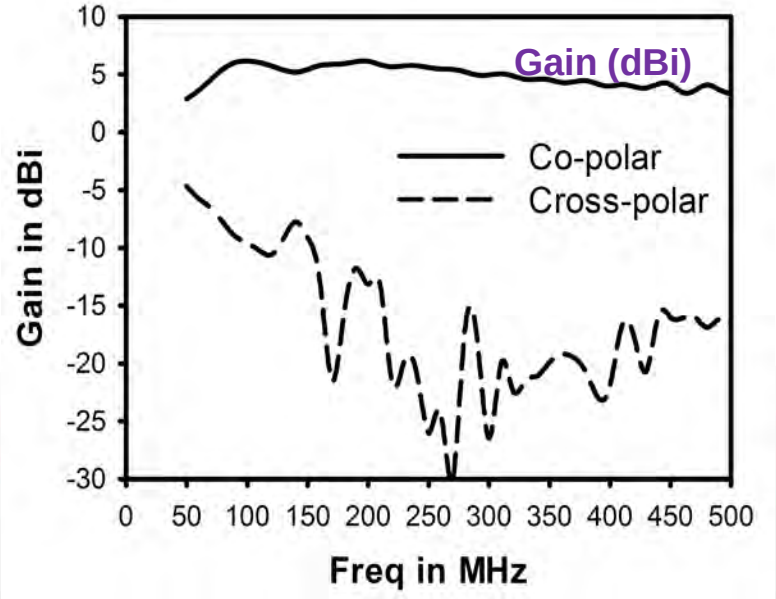
- Conical spiral with constant arms widths
  - Easier to prototype
  - More manufacturable?
- Retains many desirable sheet spiral characteristics
- Feed impedance changes as a function of arm widths
- LMR-400 coax; $\alpha = 75^\circ$; $\theta_0 = 15^\circ$



1/3 scale model of SKA-low conical wire spiral antenna

Return loss and gain: wire spiral





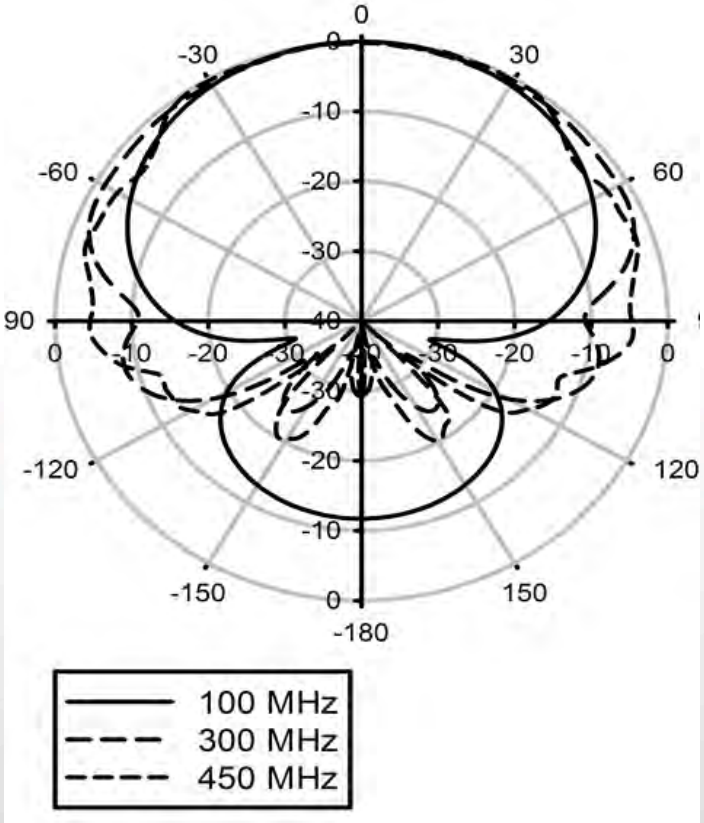
Simulation results (free space)

- 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

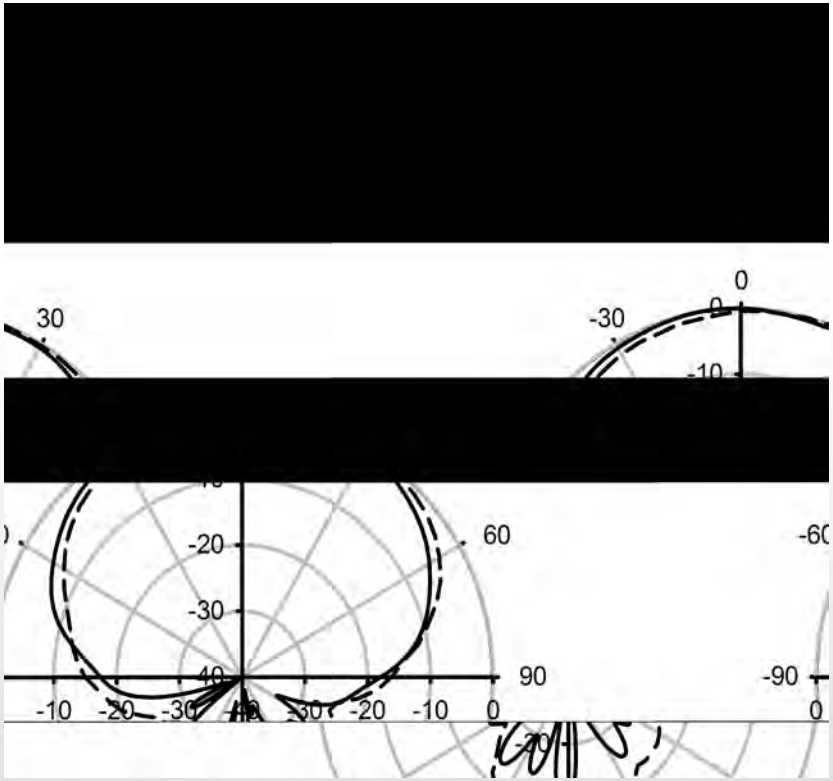
- Smooth patterns
- Backlobes < -10 dB



Radiation pattern of wire conical log spiral

Measurements of wire spiral

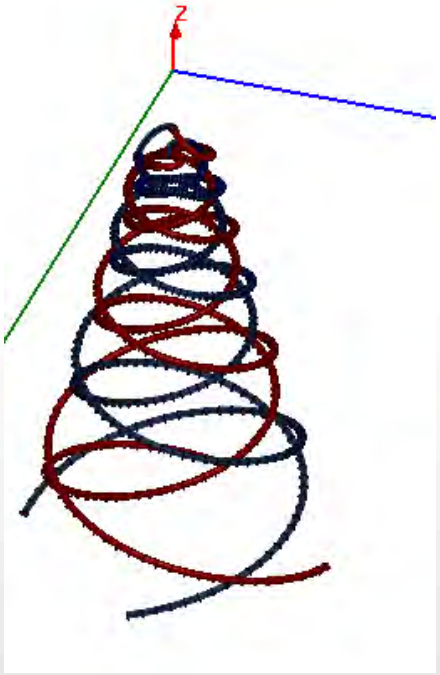
- Constructed a 6.5 : 1 frequency range, 1/3 scale prototype (210 – 1350 MHz)
- Measurements show good overall agreement with simulation
  - (within a basic measurement environment)



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

Dual-polarized wire spiral antenna

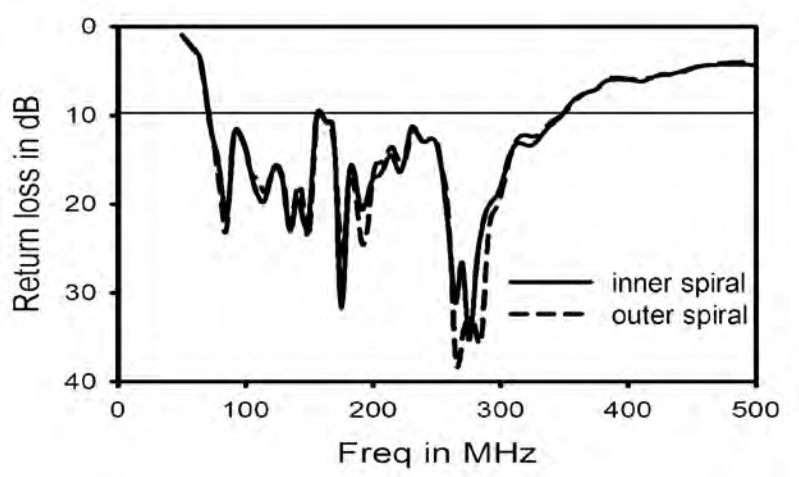
- SKA-low requires two opposite polarizations
- Wire spirals are inherently single polarized
- We could intersperse LH and RH spirals in array, but
  - More cost
  - Increases minimum packing distance → unacceptable
- Can we make a “counter-wound” dual-polarized antenna?
  - Two oppositely-polarized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



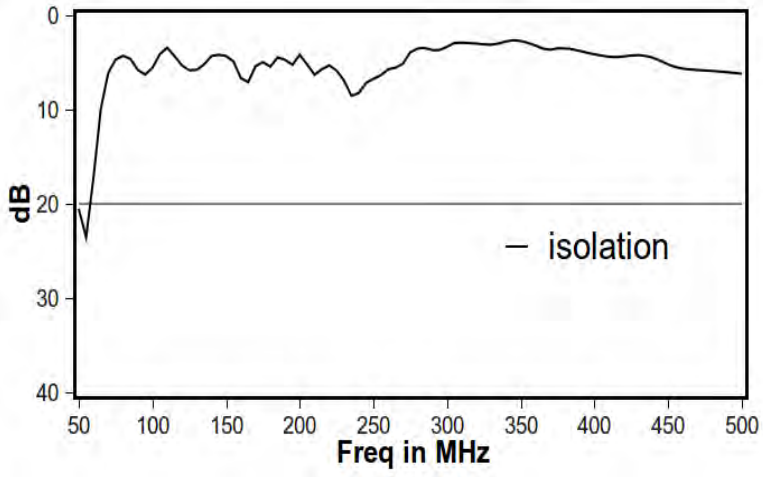
Dual-polarized wire spiral model

Dual wire spiral characteristics

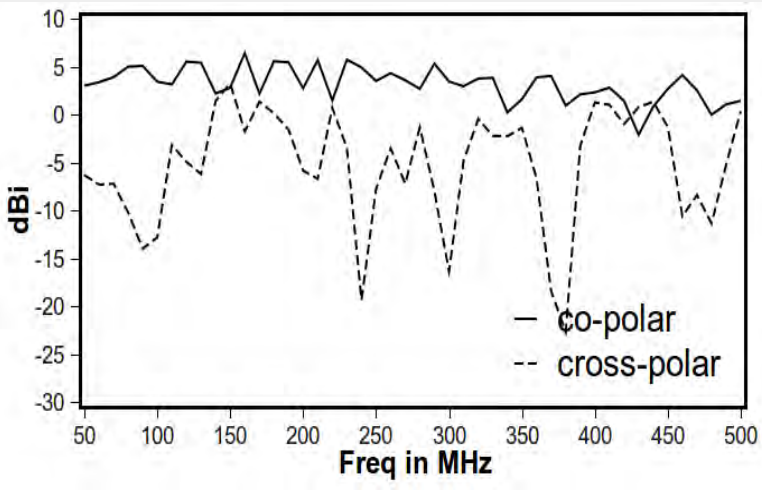
Return loss (ref. 300 ohm)



Isolation



Gain (inner spiral)

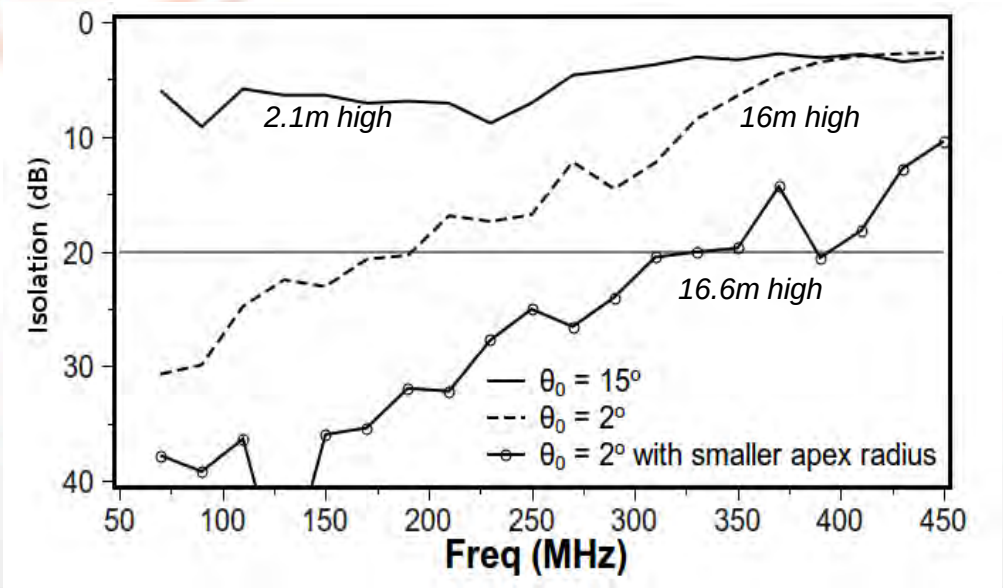


Simulation results

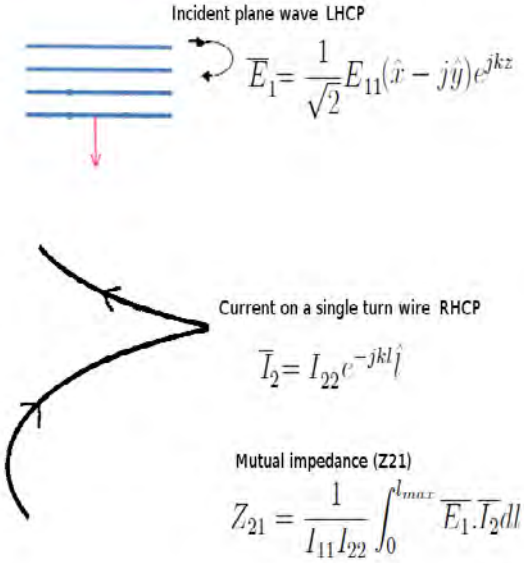
- Return loss is below -10 dB over the 70 – 350 MHz bandwidth
- Poor isolation between the two antennas → high cross polarization

Dual wire spiral: can it ever work?

1-turn RHCP spiral with a LHCP field incident

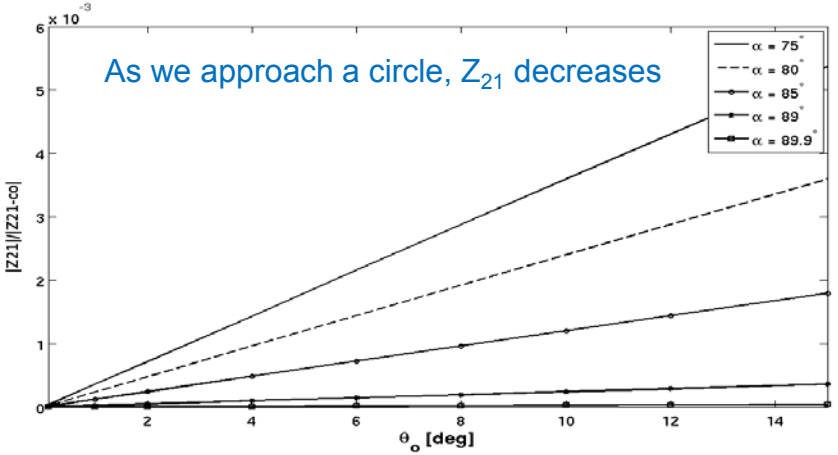


Isolation for two values of θ_0 with $\alpha = 75^o$

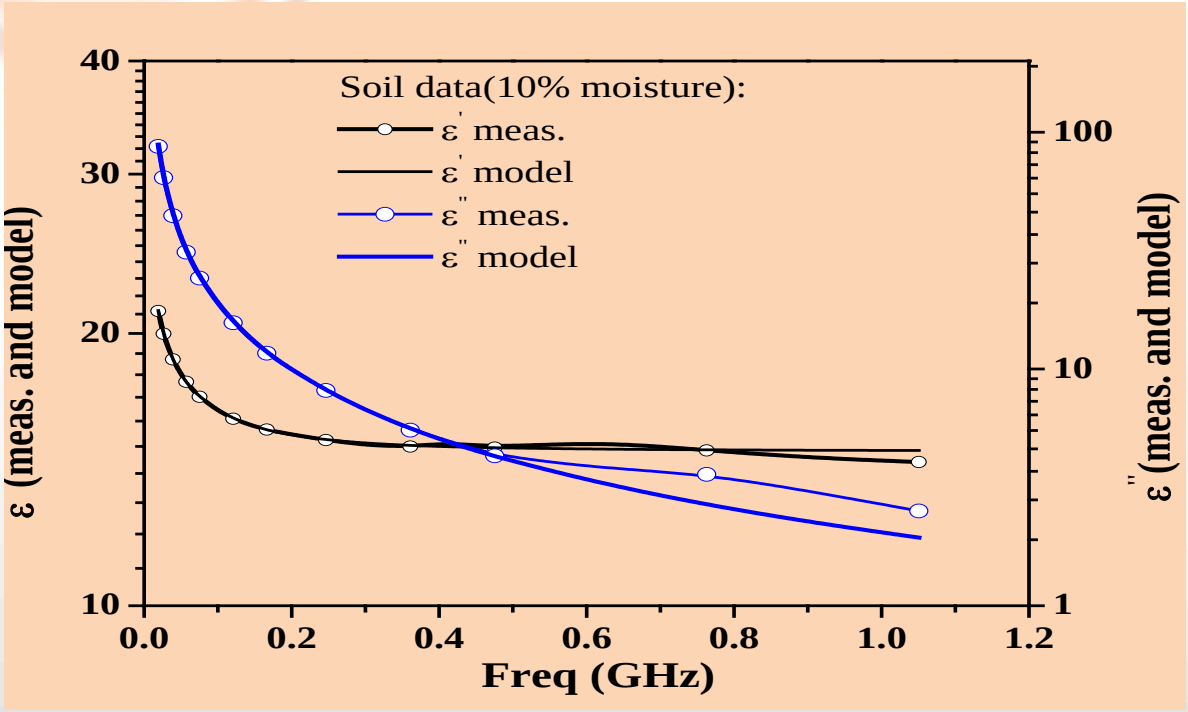


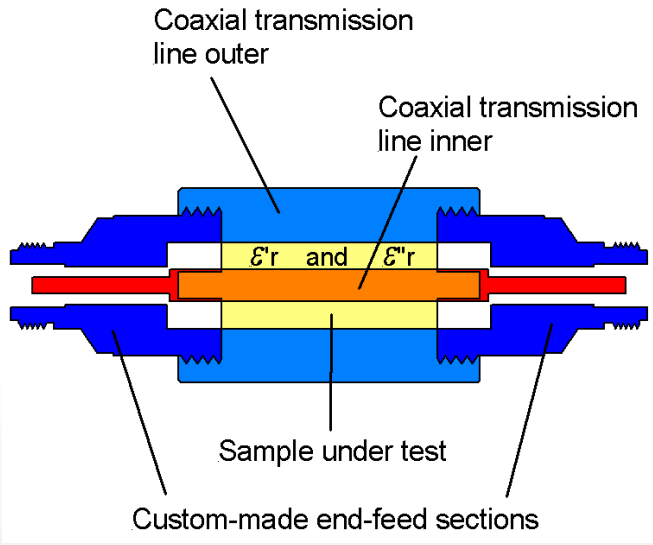
$$Z_{21-co} = \frac{-j\sqrt{2}\pi}{k}\frac{E_1}{I_{11}} \quad (\text{when } \phi_{max} = 2\pi)$$

- Higher isolation with low θ_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

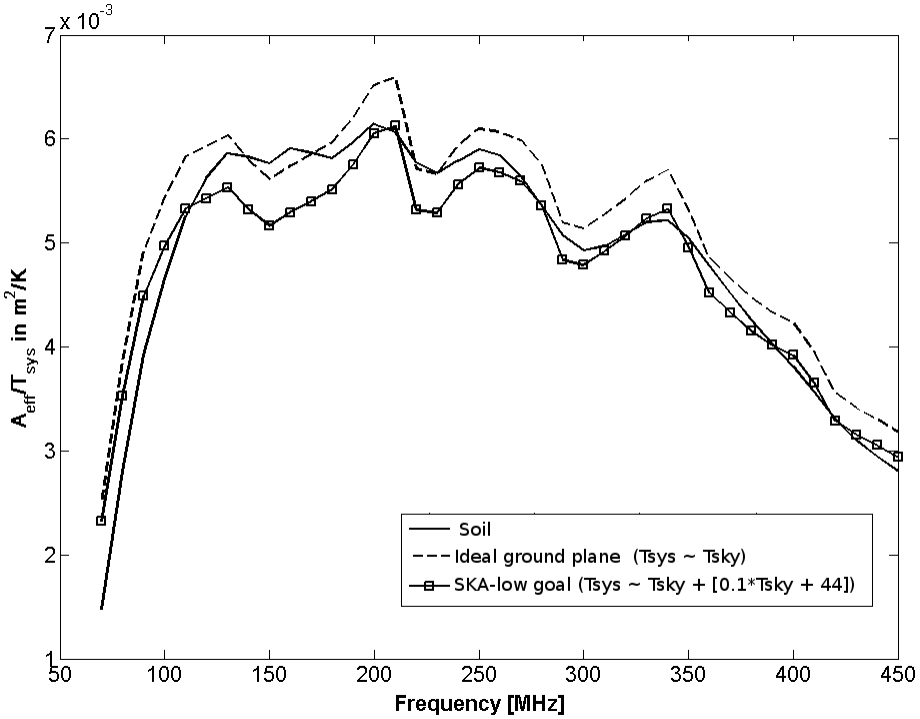




- Measured relative permittivity of 5 soil samples (courtesy CSIRO)
- Permittivity measurements with different moisture contents
- Fitting with dispersive model (Debye 2 parameter model)

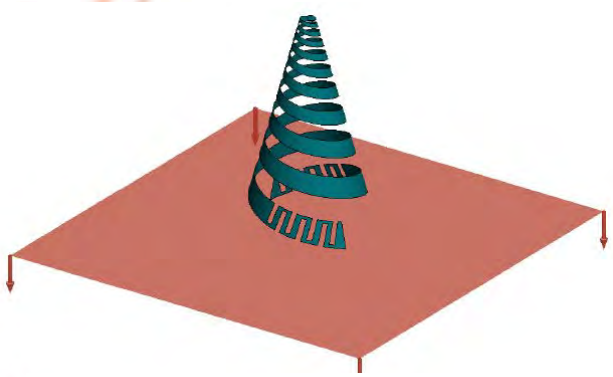
Do we need a ground plane?

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

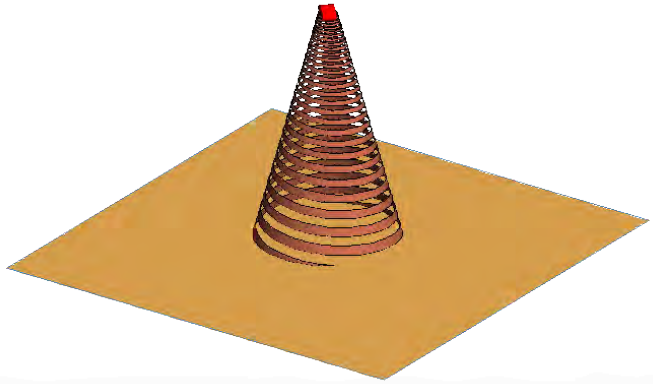


- Spiral with a metallic ground plane has higher sensitivity than SKA-low goal
- Spiral over the soil does not meet goal below 110 MHz, but is close enough to warrant detailed performance and cost trade-off
- Highly-directive SKA-low antennas (like the conical spiral) may not need a metallic ground plane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

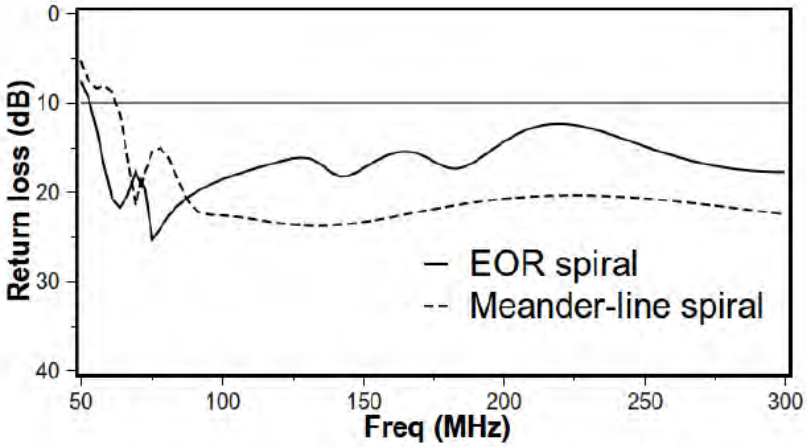
EoR spiral antenna:

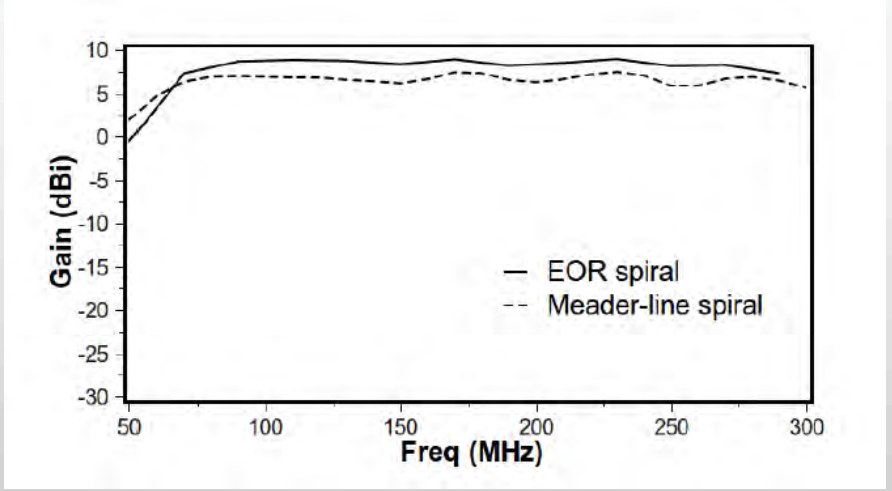


Meander conical spiral antenna



Conical spiral antenna





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