Design Considerations for Radio Telescopes

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@SciBry

#DSS2017
New Technologies for Canadian Observatories (NTCO)

› New six year program funded by NSERC CREATE

› Goal: address the need for technological innovation in the next generation of astronomical instrumentation

› Focus: new detector, optics/photonics, focal plane, and manufacturing technologies for astronomical instrumentation and industrial applications

› Members: U. Victoria, U. Toronto, McMaster, Laval, NRC

› Student stipends and funding!

› Courses and training in professional skills and development

› 20% of academic time conducting research in Canadian industry

› More information: ntco@uvic.ca or http://bit.ly/NTCO_CREATE
My Story
My Career in A Nutshell

Credits: NASA Chandra ; NASA ; Rainer Beck / Andrew Fletcher / MPIfR / STScI ; SKA
# Highs and Lows (I)

## Table 1C

Analytic Expressions for \( L(t) \) Case E and NE

<table>
<thead>
<tr>
<th>Time Range</th>
<th>Frequency Range</th>
<th>Analytic Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t &lt; t_0 )</td>
<td>All ( \nu )</td>
<td>( L(t) = 1 \times 10^{48} \times t^{-2/3} )</td>
</tr>
<tr>
<td>( t_0 &lt; t &lt; \min { t_1, t_2 } )</td>
<td>All ( \nu )</td>
<td>( L(t) = 4 \times 10^{48} \times t^{-1/3} \times \frac{1}{1 + \beta \nu} )</td>
</tr>
<tr>
<td>( t_1 &lt; t &lt; t_2 )</td>
<td>All ( \nu )</td>
<td>( L(t) = 4 \times 10^{48} \times t^{-1/3} \times \frac{1}{1 + \beta \nu} )</td>
</tr>
<tr>
<td>( t_2 &lt; t &lt; t_3 )</td>
<td>All ( \nu )</td>
<td>( L(t) = 4 \times 10^{48} \times t^{-1/3} \times \frac{1}{1 + \beta \nu} )</td>
</tr>
<tr>
<td>( t_3 &lt; t &lt; t_4 )</td>
<td>All ( \nu )</td>
<td>( L(t) = 4 \times 10^{48} \times t^{-1/3} \times \frac{1}{1 + \beta \nu} )</td>
</tr>
<tr>
<td>( t_4 &lt; t &lt; \infty )</td>
<td>All ( \nu )</td>
<td>( L(t) = 4 \times 10^{48} \times t^{-1/3} \times \frac{1}{1 + \beta \nu} )</td>
</tr>
</tbody>
</table>

\( t_0, t_1, t_2, t_3, t_4 \) are the characteristic times, \( \beta \) is the Doppler factor, and \( \nu \) is the frequency.

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**Credits:** Reynolds & Chevalier (1984); Kristen Chirico / Buzzfeed
Highs and Lows (II)

February 20, 2005

Dying Star Flares Up, Briefly Outshining Rest of Galaxy

By KENNETH CHANG

For a fraction of a second in December, a dying remnant of an exploded star let out of a burst of light that outshone the Milky Way’s other half-trillion stars combined, astronomers announced Friday.

Even on Earth, half a galaxy away, the starburst was one of the brightest objects ever observed in the sky, after the Sun and perhaps a few comets. The magnitude of the event caught most astronomers by surprise.

"Whoppingly bright," said Dr. Bryan M. Gaensler, an astronomer at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass. "It gave off more energy in 0.2 seconds than the Sun does in 100,000 to 200,000 years."
Radio Telescopes

› Sky coverage

› Point-source sensitivity vs surface brightness sensitivity

› Angular resolution and confusion

› Snapshot coverage vs full-synthesis coverage

› Frequency and bandwidth

› Largest angular scale, field of view and survey speed

› Spectral resolution, time resolution & data rate

› Polarimetry

CSIRO; NRAO/AUI, Natasha Hurley-Walker; © Top Foto, Assen; NRAO/NAOJ/ESO
Supernova Remnants

› Fossil record of explosion and progenitor star
› Illumination of the invisible interstellar medium
› Shock physics and acceleration of cosmic rays

› Faint non-thermal (\(S \sim \nu^{-0.5}\)), continuum emission
  - low frequencies (\(\lesssim 5\) GHz)
  - broad bandwidth (\(\sim 1\) GHz)
  - coarse spectral resolution (\(\sim 10\) MHz)

Cassiopeia A
(Stage et al. 2006)

SNR 1006
(Cassam-Chenai et al. 2008)
Supernova Remnants II

- Generally small angular diameter, (e.g. $\sim 3 - 60$ arcmin across)
  - $\lambda = 0.2 \text{ m}, D = 50 \text{ m}: \theta \approx 1.2 \frac{\lambda}{D} = 17'$
  - array, not single dish

- Complex structure on many angular scales
  - good u-v coverage needed
  - many baselines
    (many antennas, long tracks, multiple arrays)
  - integration time probably not set by sensitivity!

- Suitable telescopes:
  VLA (compact configuration),
  DRAO Synthesis Telescope

Andrew Gray
MPIfR, NRAO/AUI. CGPS
VLA in D configuration
(Ceravolo Images)
Single Dish / Array Combination

› Longest baseline sets smallest scale of image
  … but shortest baseline gives largest scale of image!
→ interferometer misses large-scales; fluxes and spectra wrong
→ need to combine with single-dish data to see full picture
Galactic Hydrogen

› “HI” is an emission/absorption line of neutral hydrogen at 1420.406 MHz (21 cm)

› Traces distribution, temperature, density of cold and warm atomic gas

› Doppler shift gives Galactic rotation and Galactic structure

› Narrow bandwidth (~10 MHz = 2000 km/s), high spectral resolution (4 kHz = 0.8 km/s)

› Large-scale emission: single dish (e.g. Parkes)

› Small-scale emission: dish + array (Parkes+ATCA)
Array Configuration

› Many arrays are re-configurable (e.g. VLA, ATCA, WSRT, DRAO)

› Extended arrays:
  - high resolution, slow survey speed, poor surface brightness sensitivity
  - e.g., observations of individual distant radio galaxies

› Compact arrays
  - coarse resolution, rapid survey speed, high surface brightness sensitivity
  - e.g., survey of large nearby galaxy

› East-west arrays
  - need coverage over 12 hours

› Two-dimensional arrays
  - single “snapshot” may be sufficient

› Independent of config: field of view, theoretical point-source sensitivity
Radio Galaxies

- Large-scale interaction of supermassive black holes with their environments
- Conversion of gravitational energy into relativistic particles, electrical currents, kinetic energy
- Feedback: regulates star formation in host galaxy
- Bright non-thermal \((S \sim \nu^{-0.7})\) continuum
  - range of frequencies \((\sim 0.1 - 10 \text{ GHz})\)
  - broad bandwidth
  - coarse spectral resolution \((\sim 10 \text{ MHz})\)
  - usually small in scale: need long baselines, \(\sim\text{arcsec resolution}\)
  - considerations: \(u-v\) coverage, dynamic range
Confusion & Sensitivity

- Ideally, sensitivity set by the radiometer equation
  \[ N = \frac{T_{sys}}{\sqrt{\Delta \nu_{RF} \tau}} \]
  - bandwidth, integration time, system temperature

- But beware confusion!

- Classical confusion (“forest for the trees”)
  - at low angular resolution, sensitivity is **not** set by radiometer equation, but by “confusing” sources!
  - confusion level is function of frequency, resolution
  \[ \rightarrow \text{know your faint foregrounds/backgrounds} \]
  \[ \rightarrow \text{set resolution so that confusion < sensitivity} \]

- Sidelobe confusion (dynamic range limitations)
  - if some sources are bright, bad calibration will mess up the rest of the image
  \[ \rightarrow \text{know your faint foregrounds/backgrounds} \]
  \[ \rightarrow \text{u-v coverage and calibration strategy} \]
  affect sensitivity

ATLAS (Norris et al. 2006)
MGPS (Green et al. 1998)
André Offringa
Dynamic Range

M87 -- From 200,000 Light-Years to 0.2 Light-Year

Credit: Feizel-Glover (NRAO), John Silverio (STScI) and colleagues.
The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

NRAO / AUI
Quasar Variability & Scintillation

- Intrinsic variability: small-scale structure in jet and accretion disk around black hole
- Scintillation: refraction effects probe turbulence in invisible foreground gas in the Milky Way
- Intrinsic effects: high freq ($\gtrsim 5$ GHz)
- Propagation effects: low freq ($\lesssim 5$ GHz)
  - frequency dependent
  - coarse resolution ($\sim 10$ MHz)
- Sources unresolved, just want fluxes
  - bright: single dish OK
  - faint: array needed to overcome confusion; sub-arrays may be efficient

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Gaensler & Hunstead (2000)
Extragalactic Hydrogen I

› Structure, rotation, dynamics, turbulence of other galaxies
› Trace assembly of galaxies over cosmic time
› Individual galaxies: array, single pointing
  – high angular resolution (arrays)
  – narrow bandwidth (~10 MHz)
  – intermediate spectral res (~20 kHz)
› Large volumes: single dish, survey
  – low angular resolution
  – broad bandwidth
    \((\Delta \nu = 100 \text{ MHz} \rightarrow \Delta z = 0.08)\)
  – intermediate spectral res (~20 kHz)
Extragalactic Hydrogen II

- Hydrogen in absorption
  - produced by galaxy along line of sight to bright background continuum source
  - signal-to-noise independent of distance
  - can trace galaxies to high redshift
  - “needle in a haystack” problem in x, y, ν

- New frontier: focal plane arrays with ultra-wide fields of view and broad bandwidths
  - ASKAP: 700–1000 MHz over 30 deg²
Pulsars

› Tests of General Relativity, binary evolution and high-energy astrophysics

› Precision probe of interstellar medium

› Extremely non-thermal ($S \sim \nu^{-2}$) continuum
  – low frequencies ($\lesssim 2$ GHz)

› Brief (point-like!) signal, dispersed by interstellar medium
  – high time resolution ($<1$ ms)
  – broad bandwidth, high spectral resolution
Pulsars II

› Imaging & resolution unimportant, driven only by sensitivity
  – biggest possible collecting area (single dish → array)
  – integration time set by signal-to-noise, binary motion
  – field of view hugely important for searches
  – field of view less important for timing

› Pulsar timing arrays
  – good sky coverage needed
Pulsar Astrometry

- Distances: Galactic structure
- Velocities: supernova physics
- Parallax: $d = 1 \text{ kpc}$
  \[ \pi = \frac{1}{d} = 0.001 \text{ arcsec} \]
- Proper motion: $V = 100 \text{ km/s}$
  \[ \mu = \frac{V}{d} = 0.02 \text{ arcsec/year} \]
- At 5 GHz, $\lambda = 0.06 \text{ m}$ and need $\theta = 0.001 \text{ arcsec}$
  \[ D \approx \frac{1.2}{\lambda / \theta} = 15000 \text{ km} \]

Chatterjee et al. (2004)

“Guitar Nebula” (Palomar Observatory)
Star Formation & Proto-stars

› Morphology, time scales, dynamics uncertain
› Process of planet formation
› Thermal emission from cold dust
› Molecular lines
› Compact structures (≪ 10 arcsec)
  → high frequencies (e.g., 350 GHz)
  → array with baselines ≥ 500 metres
› High-altitude site, dishes with very high surface accuracy and pointing stability

ALMA (ESO/NAOJ/NRAO)

Codella et al. (2014)
The Murchison Widefield Array and the SKA

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#DSS2017

on behalf of the MWA collaboration, and with thanks to the Wajarri Yamatji people
Many small antennas or focal plane arrays
- MWA, LOFAR, ASKAP, SKA-Low
- wide fields (1000 deg$^2$), rapid surveys (entire sky every night), enormous data rates (70 TB/s)
  → dedicated supercomputers
  → new detection algorithms
  → real-time processing
Epoch of Reionization

- Spectra of distant quasars, polarisation of cosmic microwave background
  - Universe rapidly changed from neutral to ionised around 13 billion years ago
- Hydrogen has spectral line at 1420.406 MHz
- Objective: detect heavily redshifted hydrogen (frequencies ~100-200 MHz) and watch this cosmic phase transition occur!

You are here ($t = 13.8$ billion years)
Epoch of Reionization II

- Universe rapidly changed from neutral to ionized ~13 billion years ago
- Redshifted hydrogen emission line should appear all over the sky at ~100-200 MHz, but not above
- Expected scale ~ 1 degree, but array needs to be calibrated, foreground structures need to be removed
  → condensed array within ~300 metres, with outriggers
  → calibration, foregrounds still very challenging!

Furlanetto et al. (2004)
Murchison Radio-Astronomy Observatory

Murchison Shire Boundary

Population Density: 0.002 km$^{-2}$

Steven Tingay
A Unique Radio-Quiet Environment

Sydney
Pop. 4.8 million

Narrabri
Pop. 5,900

Murchison Shire
Pop. 114
Murchison Widefield Array

- 128 tiles, 20 m² each, spread over 3 km
- Can observe 30 MHz within range 80–300 MHz (very low!)
  → angular resolution ~2 arcmin over 1000 deg²
  → very bright sky, numerous foregrounds, sun, moon, ionosphere, real-time calibration, ...
  → epoch of reionization

- August 2013: Commenced operations
- July 2017: 15 petabytes (15 million gigabytes) of data
- late-2017: Commencement of MWA phase 2
  → 2x angular resolution, 5x sensitivity
  → cosmic web
- 2022: SKA1-Low
Wide-Field Radio Astronomy

- Many small antennas or focal plane arrays
  - MWA, LOFAR, AperTIF, ASKAP, SKA
  - wide fields (1000 deg²), rapid surveys (entire sky every night), enormous data rates (70 TB/s)

  → dedicated supercomputers
  → new detection algorithms
  → real-time processing
Challenge: Ionosphere

- Spatial and temporal fluctuations in plasma density produce position shifts, defocusing, scintillation

- Huge instantaneous MWA field of view (~1000 deg^2)
  - track 1000 source positions at 2-minute cadence
  - map vector offsets as function of time (Loi, Gaensler et al. 2015a, 2015b)
  - robust correction for ionospheric refraction

- Organized strips of alternating position shifts
  - bands of underdensity and overdensity
  - aligned with projection of Earth’s magnetic field
  - stereoscopic imaging: $h = 570 \pm 40$ km
  → cylindrical density ducts, coupling ionosphere and plasmasphere via whistler waves
  → direct 4D visualization of bulk plasma drifts

Loi et al. (2015a, 2015c)
Galactic and Extragalactic All-sky MWA Survey (GLEAM)

MWA GLEAM survey
(Wayth et al. 2015; Hurley-Walker et al. 2015)

- 80-230 MHz
- Entire sky south of +25°
- 2 arcmin resolution
- $10^5$ sources down to 0.1 Jy
- Commensal transient survey
Great Observatories for the Next Decade

E-ELT/TMT/GMT: optical/IR

James Webb Space Telescope: NIR

Square Kilometre Array: cm/m

Atacama Large Millimetre Array (ALMA): mm/submm
What is the SKA?

Phase I:
- SKA1-Low: 130,000 element Low Frequency Aperture Array
  - Phase I: 2022
- SKA1-Mid: 200 dishes

Phase II:
- SKA2-Low: 1,000,000 element Low Frequency Aperture Array
  - Phase II: 2030
- SKA2-Mid: 2500 dishes

Science
- Cosmic Dawn & Reionization
- Cosmology & Galaxy Evolution
- Pulsars
- Cosmic Magnetism
- Cradle of Life

Frequency Bands:
- 50 MHz
- 100 MHz
- 1 GHz
- 10 GHz
Summary

› Single dish
  – total fluxes, pulsars, hydrogen surveys

› Compact arrays
  – extended/diffuse objects, wide area maps

› Extended arrays
  – detailed studies of individual small objects

› Low frequency dipoles
  – all-sky surveys, reionization

› The future: the Square Kilometre Array
  – we have spent 25 years designing this next-generation radio telescope!