### Long Wavelength Interferometry



#### ASTR 423 Radio Astronomy

#### Announcements – The Sprint to the Finish

- Exam2 average: 84% good job
- Course evaluations: 10% not as good, but not too late
- May 5; teams CasA and CygA
- May 7; teams Sag A and M87
- May 14; teams Jupiter1, Jupiter2, Starlink
- Presentations should use slides (powerpoint, keynote, etc.) and aim for 21+10 (talk + Q&A) Everybody in the group needs to take a turn speaking
- May 16 Written reports due





#### Science - All-Sky Survey



**35 MHz** Dwarakanath et al. 1990

38 MHz Turtle et al. 1962

45 MHz Alvarez et al. 1997; Maeda et al. 1999

> 81 MHz Bridle 1967



85 MHz Landecker & Wielebinski 1970







#### The Sky 35-80 MHz

Dowell et al. 2017

+ New Low Frequency Sky Model generator



## Confusion

First radio telescopes operated at long wavelengths with low spatial resolution and very high system temperatures

Radio astronomy quickly moved to higher frequencies with better spatial resolution and lower system temperatures

#### $\theta \sim 1$ ', rms ~ 3 mJy/beam

#### $\theta \sim 10^{\circ}$ , rms $\sim 30$ mJy/beam



### Low Frequency In Practice: <u>Not Easy!</u>

• Bandwidth smearing

Distortion of sources with distance from phase center

• Interference:

Can be severe below 5 GHz

• Phase coherence through ionosphere

Corruption of coherence of phase on longer baselines

• Finite Isoplanatic Patch Problem:

Calibration changes as a function of position

•Large Fields of View:

Non-coplanar array (u, v, & w)

Large number of sources requiring deconvolution

- Time-variable primary beam
- Lots of sources Large Number of elements required

### Large Fields of View (FOV) I

Noncoplanar baselines: (*u*,*v*, and *w*) - Cotton, SI ch 17

Important if FOV is large compared to resolution

=> in AIPS multi-facet imaging, each facet with its own  $\theta_{synth}$ 

• Essential for all observations below 1 GHz and for high resolution, high dynamic range even at 1.4 GHz

Requires lots of computing power and disk space

• AIPS: IMAGR (DO3DIMAG=1, NFIELD=N, OVERLAP=2), CASA : w-projection

Example: VLA B array 74 MHz: ~325 facets

> A array requires 10X more:  $\sim 3000$  facets  $\sim 10^8$  pixels

## **Targeted Faceting**

enormous processing required to image entire FOV
reduce processing by targeting facets on selected sources (still large number!)
overlap a fly's eye of the central region and add individual outliers

• AIPS: SETFC



#### AIPS Tip:

- Experience suggests that cleaning progresses more accurately and efficiently if EVERY facet has a source in it.
- Best not to have extended sources spread over too many facets
- => often must compromise

### Large Fields of View (FOV) II

#### Calibrators:

 Antenna gain (phase and amplitude) and to a lesser degree bandpass calibration depends on assumption that calibrator is a single **POINT** source

• Large FOV + low freq. = numerous sources everywhere

 At 330 MHz, calibrator should dominate flux in FOV: extent to which this is true affects absolute positions and flux scale

=> Phases (but not positions) can be improved by self-calibrating phase calibrator

=> Always check accuracy of positions

 Must use source with accurate model for bandpass and instrumental phase <u>CygA</u>, CasA, TauA, VirgoA

## **Ionospheric Structure:**



• Waves in the ionosphere introduce rapid phase variations (~1°/s on 35 km BL)

• Phase coherence is preserved on BL < 5km

• BL > 5 km have limited coherence times

• Historically limited capabilities of low frequency instruments

## **Ionospheric Effects**

Wedge Effects: Faraday rotation, refraction, absorption below ~ 5 MHz (atmospheric cutoff) Wave and Turbulence Effects: Rapid phase winding, differential refraction, source distortion, scintillations



<u>Wedge</u>: characterized by TEC =  $\int n_e dl \sim 10^{17} \text{ m}^{-2}$ 

Extra path length adds extra phase  $\Delta L \alpha \lambda^2 * TEC$  $\Delta \phi \sim \Delta L / \lambda \sim \lambda * TEC$ 

<u>Waves</u>: tiny (<1%) fluctuations superimposed on the wedge

> The wedge introduces thousands of turns of phase at 74 MHz

Interferometers are particularly sensitive to difference in phase (wave/turbulence component)

### **Oth Order Correction: Refractive Wander**



Right Ascension Offset (Arcseconds)

- The large-scale ionospheric refraction shows considerable variability
  - Shown at the left 74MHz referenced to 1400MHz images
- Large Scale Ionospheric Structure -> simple phase shift
- Solution use known phase centers to shift images to compensate

### **Antenna Phase as a Function of Time**

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A wide range of phenomena were observed over the 12-hour observation => MYTH: Low freq. observing is better at night. Often daytime (but not dawn) has the best conditions

### **Ionosphere Overview**

- What is the ionosphere?
  - Partially ionized gas (i.e. a plasma) that envelops the earth and forms the interface between the atmosphere and space:

<u>*Plasma*</u>: quasineutral gas of charged and neutral particles <u>*lonizing source*</u>: UV light, x-rays and cosmic rays

- Why do we care about the ionosphere?
  - Many reasons, but for our purposes today, it affects radio wave propagation
- How do we detect the ionosphere?
  - Sounders (i.e. ionosondes)
    - Ground-based
    - Space-based
  - Radar
    - Coherent Incoherent Scatter Radar (ISR)
  - Satellites (GPS, etc.)
  - Rockets
  - Etc.





### History

- On December 12, 1901, Marconi received a signal in St. John's
   Newfoundland that had been sent from Cornwall, England (500 kHz): Nobel
   Prize in physics in 1909 for using EM radiation for radio communication
  - Problem: EM radiation travels in straight lines and maximum distance determined by Line-of-Sight (LOS). How could Marconi have "heard" the signal?
  - Solution: Heaviside and Kennely in 1902 proposed that a conducting layer existed in upper atmosphere that reflects EM signals



 In 1924, Appleton developed the ionosonde (ground-based sounding) and proved existence of <u>ionosphere</u>. Awarded Nobel Prize in physics in 1947

#### **Ionospheric Layers**

- Ionospheric layers independently produced by absorption of solar radiation by specific constituents of neutral atmosphere
- D region
  - 60-90 km, dynamics dominated by neutral atmosphere
  - Ions are NO<sup>+</sup> produced by radiation at 121.5 nm
- E region
  - 90-130 km, peak near 110 km
  - Ions are O<sub>2</sub><sup>+</sup> and NO<sup>+</sup> produced by UV radiation in the 100-150 nm range, and solar X-rays in the 1-10 nm range
- F region ( $F_1$  and  $F_2$ )
  - Above 130 km (typically caps at 2000 km)
     F<sub>1</sub> peaks near 170 km, F<sub>2</sub> peaks near 250 km
  - Ions are mainly O<sup>+</sup> from photons in the 17-91 nm range



#### **Ion Production - Photoionization**

- Ionospheric peaks generated by:
  - Incoming solar radiation intensity increases with height
  - Neutral density decreases with height

 Ionospheric layers generated by solar radiation acting on different compositions of atmosphere with height



- Chapman theory (developed in 1927) describes ion production as a function of height assuming:
  - Details of photon absorption hidden in a radiative-absorption cross section,  $\boldsymbol{\sigma}$
  - Ion production depends only on amount of radiative energy absorbed

#### **Density from Ion Loss and Production**

#### • Ion loss

- Ionospheric electrons disappear by thre types of recombination:
  - 1) Radiative:  $e + X^+ \rightarrow X + hv$
  - 2) Dissociative:  $e + XY^+ \rightarrow X + Y$
  - 3) Attachment:  $e + Z \rightarrow Z^{-}$
- Recombination rates depend upon:
- Loss =  $L = \alpha n_e n_i$ , where  $\alpha$  is a recombination coef. determined by empirical and theoretical models



#### Incoherent and Coherent Echoes over Jicamarca



#### When does a Radio Wave get Reflected by Plasma?<sup>20</sup>



Real-world examples

You need a radio frequency of 2 MHz to reflect from the E-region (10<sup>5</sup> el/cm<sup>3</sup>)

You need a radio frequency of 9 MHz to reflect from the F-region (10<sup>6</sup> el/cm<sup>3</sup>)

But these are <u>gross</u> over-simplifications, as the ionosphere is extremely dynamic and variable!

## **Ionospheric Absorption**



beam 1: off-source, pointed at north celestial pole beam 2 and 3: fixed points along Cyg A track beam 4: tracking Cyg A <sup>21</sup>



## Passive Over the Horizon Radar



#### **Ionospheric GPS Data**

- Recall that GPS satellites can "probe" ionosphere by transmitting at two different frequencie simultaneously
  - Total Electron Content (TEC) is integrated density along line of sight:  $TEC = \int n_e ds$



#### **Ionospheric Variability - Time**



### **Ionospheric Variability - Location**

- Auroral
  - Field lines coupled to magnetosphere
  - B<sub>z</sub> field perpendicular to Earth
- Equatorial
  - B<sub>x</sub> field parallel to Earth
    - $E_z \rightarrow$  zonal drifts (large)
    - $E_y \rightarrow$  vertical drifts (small but important)

Auroral Oval South





Copyright 1899, Northwest Research Associates, Inc.

#### • Mid-Latitudes

- Buffer between low- and high-latitude processes (both E fields and neutral winds penetrate here, as well as equatorial plasma streams)

#### **Current Research - Sporadic-E**

- <u>Sporadic-E:</u> dense layer of ionization in E-region that can reflect radio frequencies up to 225 MHz
  - Why is it most prevalent in summer?
  - What causes intermediate sporadic-E?
  - What causes long-lived intense sporadic-E layer? (heavy metals deposited by meteoroids?)



## **Sporadic E**



## Sporadic E



#### Obenberger et al. 2021

## Sporadic E



#### Obenberger et al. 2021

### LWA Swarm Concept (2020)





- Goal of 3 existing full stations (•) plus ~10 LWA mini stations (•), baselines up to 2500 km for resolution 0.5" at 80 MHz with 5 mJy sensitivity
- Cost is ~\$7M including 1 year of operations

Two New Mini stations funded by AFOSR/DURIP: Texas Tech – PI Tom Maccarone ASU – PI Judd Bowman





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Swarm Now No OV V (Km)

-1000

8 2000

-1000





0

1000

2000

## VLA 50-86 MHz

New 4 band feeds (MJP) 4 meter band: 50-86 MHz All 28 installed by 2019



# ELWA (u,v)-coverage and images



## ELWA: 'Good' Baselines



VLA#2 – VLA#10

VLA#26 - LWANA

## ELWA 'Bad' Baselines



VLA#4 – VLA#19

VLA#11 – VLA#13

### PSR B1919+21

- Test observation on Nov 03<sup>rd</sup> 2016, 20 min
- 12 antennas (A config.) + LWAI
- 16 MHz bandwidth/4 bit



LWAI 256 dipoles

#### VS.

#### VLA ant I 8, a 25m dish with MJP

## Great Balls of Fire!

#### 140121:7:43:08 Obenberger et al. 2014, 2016 Light curves of the brightest transients 6000 5000 4000 Flux Density in Jy 3000 2000 1000 -1000 -100 100 150 -50 50 Seconds

### Meteors – by reflection at 55.25 MHz



2014-06-18 02:59:54



### Meteors – by reflection







### Meteors – by Emission







## Two views of the sky







## Meteors – Persistent Trains



#### Cordonnier et al. 2024, 2025

## Meteors – Persistent Trains





Cordonnier et al. 2024

#### Meteor Radio Afterglows and Persistent Trains

t = 10 s



t = 20 s



t = 30 s



#### Obenberger et al. 2020

t = 40 s



t = 50 s

#### **Maximum Pixel**



## Meteors – Persistent Trains



Cordonnier et al.

#### **High Resolution Observations of an MRA with OVRO-LWA – MRA2**





## **Coronal Mass Ejection**



## **Catching a Coronal Mass Ejection**



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## **Catching a Coronal Mass Ejection**



## **Catching a Coronal Mass Ejection**

