Astrometry goes back over 5000 years!

Island of Malta
Ggantija ~3500 B.C.
Mnajdra ~3200 B.C.

Mnajdra solar alignments

Mnajdra, Malta

©C.S. Jacobs, used by permission
Celestial Reference Frames

Christopher S. Jacobs
Jet Propulsion Laboratory, California Institute of Technology
5 March 2013
I. **Concepts and Background:**
   A. What is a Reference frame? Concepts, uses, desired properties
   B. Networks: The instruments used to build the frame
      - ad hoc, VLBA, EVN, Global, DSN, LBA, AuScope, etc.
   C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.
      1. Precession, proper motion, nutation, parallax
      2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

II. **Celestial Frames built using VLBI**
   A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
   B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
   C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

III. **The Path to the Future:**
   A. Error Budgets: a tool for allocating resources for improvement
   B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
   C. ICRF-3: the next standard radio frame
   D. Gaia: an optical frame with high accuracy, billion sources
I. A. Concepts for Celestial Frames

1. **Questions:**
   - Why do we need reference frames? Celestial Frames?
   - Time, positions, velocities

2. **The Celestial Frames**
   - Terrestrial: Azimuth, Elevation
   - Equatorial plane: Right Ascension & Declination
   - Ecliptic Plane: Ecliptic Longitude & Latitude
   - Galactic Plane: Galactic Longitude & Latitude

3. **Inertial Frames**
   - No rotation
   - No acceleration
   - Quasi-inertial

C.S. Jacobs 5 Mar 2013
I. A.1 Why a Celestial Frame?

Questions:
Why do we need reference frames? Celestial Frames?

To measure Time, positions, and velocities

Time: The rotation of the earth

Positions & velocities:
Angular positions and distances of Quasars, galaxies, stars, planets, spacecraft
I. A.2 The Celestial Sphere

Preferred Frame changes with scale and application

- **Local terrestrial**: Elevation, Azimuth
  Local gravity or normal to horizon gives preferred direction
  Useful for antenna pointing

- **Equatorial plane**: Right Ascension & Declination
  Earth’s spin gives preferred direction

- **Ecliptic Plane**: Ecliptic longitude & latitude
  plane of solar system, planetary orbits
  useful for studying the solar system and
  inter-planetary navigation

- **Galactic Plane**: Galactic Longitude & latitude
  plane of Milky Way galaxy
  Useful for pulsars, masers, rotation curves…

- **Even larger structure**: local group of galaxies, Virgo cluster, …
I. A.2 Local Horizon: Azimuth, Elevation

- Local terrestrial: **Elevation, Azimuth**
  Local gravity or normal to horizon gives preferred direction
  Useful for antenna pointing
I. A.2 The Celestial Sphere

**Equatorial System:**
Earth’s spin axis gives preferred direction, the celestial pole

**Coordinates on the sky:**
Right Ascension (“longitude”)
Declination (“latitude”)

**Ecliptic Plane:**
Ecliptic Longitude & Ecliptic Latitude
plane of solar system useful for studying the solar system and inter-planetary navigation

Credit: http://www.daviddarling.info/encyclopedia/C/celsphere.html
I. A.2 The Celestial Sphere

- Galactic Plane: Galactic Longitude, l, & Galactic latitude, b
  Useful for pulsars, masers, rotation curves…
I. A.2 The Celestial Sphere

- How far before we get to the quasars? Even larger structures: local group of galaxies, Virgo cluster, Virgo super cluster…

~3M light years

~100M light years

Credit: Andrew Z. Colvin
http://commons.wikimedia.org/wiki/File%3AEarth%27s_Location_in_the_Universe_(JPEG).jpg
Quasars ~ Gigaparsec; Virgo cluster distance (50 Mpcs)
I. A.3 Inertial Frames

• Why an Inertial Frame?
  Make the calculations easy! Avoid Coriolis forces etc.

  No rotation

  No acceleration

• Quasi-inertial
  In real systems we have some unmodeled accelerations
  At present, VLBI doesn’t yet model acceleration toward the Galactic center, but this is being studied
  e.g. Titov et al  

• VLBI uses quasi-inertial frame with origin at the Solar System Barycenter (center of mass)
How Does VLBI Work? It’s Simple ;-)
How Does VLBI Work?

Combine signals from a Phased Array
Antennas are Mechanical Arrays

Single Large Dish is an “array” of panels aligned mechanically. Note side lobes.

Imagine removing inner panels, then beam pattern changes, sidelobes rise, but center lobe still has high resolution \( \sim \) wavelength / \( D \)
Mechanical \rightarrow \text{electrical alignment} \rightarrow \text{VLBI}

Two segments of antenna

Two separate antennas with Electrical Connection

Unconnected Antennas = VLBI
Time tag data and combine signals later at correlator

“Fringes”

Same fringes as b).

Same fringes as b).

Figure credit: H. Gush
Very Long Baseline Interferometry is a type of station differenced range

- Measures geometric delay by cross-correlating signal from two (2) stations

\[ \tau = \frac{B \cdot s}{c} \]
Outline

I. Concepts and Background:
   A. What is a Reference frame? Concepts, uses, desired properties
   B. Networks: The instruments used to build the frame
      ad hoc, VLBA, EVN, Global, DSN, LBA, AuScope, etc.
   C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.
      1. Precession, proper motion, nutation, parallax
      2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

II. Celestial Frames built using VLBI
   A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
   B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
   C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

III. The Path to the Future:
   A. Error Budgets: a tool for allocating resources for improvement
   B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
   C. ICRF-3: the next standard radio frame
   D. Gaia: an optical frame with high accuracy
I.B. Observing Networks

VLBA

S/X VCS catalog
K, Q catalogs

25-meter dishes

10 stations

Baselines up to 8000 km

No southern stations

http://www.vlba.nrao.edu/
I.B. Observing Networks: EVN

EVN

S/X-band
K-band

Inhomogeneous set of antennas

HartRAO in south

http://www.evlbi.org/
I.B. Observing Networks: Global
ESA’s Argentina 35-meter antenna adds 3 baselines to DSN’s 2 baselines

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina
# I.C. History of Astrometry

130 B.C. Hipparchus  | Precession  | 50 asec/yr  

**Telescope era:**

<table>
<thead>
<tr>
<th>Year</th>
<th>Name</th>
<th>Type</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1718</td>
<td>A.D. Halley</td>
<td>proper motions</td>
<td>1 asec/yr</td>
</tr>
<tr>
<td>1729</td>
<td>Bradley</td>
<td>annual aberration</td>
<td>20 asec</td>
</tr>
<tr>
<td>1730</td>
<td>Bradley</td>
<td>18.6yr nutation</td>
<td>9 asec</td>
</tr>
<tr>
<td>1838</td>
<td>Bessell</td>
<td>parallax</td>
<td>~ asec</td>
</tr>
<tr>
<td>1930s</td>
<td>Jansky, Reber</td>
<td>Radio astronomy</td>
<td></td>
</tr>
<tr>
<td>1960s</td>
<td>several groups</td>
<td>Very Long Baseline Interferometry (VLBI) invented</td>
<td></td>
</tr>
<tr>
<td>1970s</td>
<td>VLBI</td>
<td>sub-asec</td>
<td></td>
</tr>
<tr>
<td>1980s</td>
<td>“</td>
<td>few 0.001 asec</td>
<td></td>
</tr>
<tr>
<td>1990s</td>
<td>“</td>
<td>&lt; 0.001 asec</td>
<td></td>
</tr>
<tr>
<td>2000s</td>
<td>“</td>
<td>~0.0001 asec</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Instrument/Method</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010s</td>
<td>Gaia</td>
<td>70 μas for Vmag=18 quasar</td>
</tr>
<tr>
<td>2010s</td>
<td>ICRF-3, ESA-DSN XKa</td>
<td>20-70 μas? 0.3 Jy quasar</td>
</tr>
</tbody>
</table>
Paradigm of “Sailing by the stars”

Photo Credit: Dimitry Bobroff, www.ludmillaalexander.com

Credit for sextent/octant: en.wikipedia.org/wiki/Sextant (GNU Free Doc license)
NASA Navigation System Accuracy

1959-2015

Mariner 2 - Venus
Mariner 4 - Mars
Mariner 6, 7 - Mars
Mariner 9 - Mars
Viking - Mars
Voyager - Saturn
Voyager - Uranus
Galileo - Jupiter
Mars Observer - Mars
Mars '01 Odyssey
Mars Polar Lander
MER
MSL

1 nrad at 1 AU = 150 meters

Credit: J.E. Patterson.
How Does VLBI Work?

The Concept:

Point Source at Infinity
Point Source at Infinity as Reference Beacon

How does VLBI work?

• Point source at infinity as a direction reference

  Extragalactic “nebulae” idea from
  Laplace (1749-1827) and
  Wm. Herschel (1738-1822): in 1785
  realized that “nebulae” likely very distant

• Advantage: sources don’t move

BUT at a distance of a billion light years . . .

• The price to be paid is

  Very weak sources 1 Jy = 1.0E-26 watt/m**2/Hz
  need lots of square meters => 34 - 70m Antenna
  lots of Hz bandwidth => 0.1 to 4 Gbps
  low system temperature => Tsys = 20 - 40 Kelvin

C.S. Jacobs 5 Mar 2013
Why observe in Radio? The ‘Window’

- Water: 1.3 cm / 22 GHz
- Oxygen: 0.5 cm / 60 GHz
- L-band: 19-24 cm (GPS)
- X-band: 3.6 cm
- Ka-band: 0.9 cm
- W-band: 0.3 cm

Gamma rays, X-rays, and ultraviolet light are blocked by the upper atmosphere. Visible light and infrared radiation are absorbed by atmospheric gases and cannot be observed from Earth. Radio waves can be observed from space without atmospheric interference.

AGN Centaurus-A in X-ray, Optical, Radio

Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.);
Radio continuum image (NRAO/VLA/J.Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

C.S. Jacobs 5 Mar 2013
Active Galactic Nuclei (AGN) schematic

Schematic of Active Galactic Nuclei
Redshift $z \sim 0.1$ to $5$
Distance: billions light years

**Parallax = 0**
**Proper motion**
$< 0.1$ nrad/yr

Centroid of radiation
Gets closer to central engine (black hole)
As one goes to higher frequencies, therefore,

**Ka-band (32 GHz)**
is better than
**X-band (8.4 GHz)**

http://heasarc.gsfc.nasa.gov/docs/objects/agn/agn_model.html
Credit: C.M. Urry and P. Padovani, 1995
Source Structure vs. Frequency

S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

K-band
24 GHz
1.2cm

Q-band
43 GHz
0.7cm

Ka-band
32 GHz
0.9cm

The sources become better --->

Image credit: P. Charlot et al, AJ, 139, 5, 2010
Active Galactic Nuclei (*Marscher*)

Features of AGN: *Note the Logarithmic length scale.*

“Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core.”

Credit: Alan Marscher, ‘Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,’ Proc. of Science, VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)
GPS is not sufficient for a long term inertial frame

Orientation: Relative to what?

One must define stable (ppb) reference directions
- GPS orbits are well modelled (ppb) over ~day time periods.

But . . .
- GPS constellation node drifts over weeks. . .

Solution: Change sources from range of
GPS’ s nano-Light year to
VLBI’s Giga-Light Years
~eighteen (18) orders of magnitude!
Celestial Pole & Alignment of Axes

- VLBI determines angles between sources

- Absolute positions only weakly determined at 10-100 mas level by tidal effects (RA, dec of Sun & Moon) and atmospheric effects (elevation)

- Orientation of axes is defined at sub-mas level by convention

- Enforced by No-Net-Rotation constraint:

\[ \sum_{i=1}^{N} s \times \Delta s = 0 \]

where \( s \) direction is source unit vector

I. Concepts and Background:
   A. What is a Reference frame? Concepts, uses, desired properties
   B. Networks: The instruments used to build the frame
      ad hoc, VLBA, EVN, Global, DSN, LBA, AuScope, etc.
   C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.
      1. Precession, proper motion, nutation, parallax
      2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

II. Celestial Frames built using VLBI
   A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
   B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
   C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

III. The Path to the Future:
   A. Error Budgets: a tool for allocating resources for improvement
   B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
   C. ICRF-3: the next standard radio frame
   D. Gaia: an optical frame with high accuracy
II.B. The Transition from Optical to Radio

- Optical to Radio transition era documented in
  

- Fundamental Katalog FK5 (Fricke, 1988)
  
  http://adsabs.harvard.edu/abs/1988VeARI..32....1F
  1535 stars limited by proper motions of stars
  ~150 mas regional differences from ICRF1  http://adsabs.harvard.edu/abs/1997IAUJD...7E..24M

- IAU called for a move to Active Galactic Nuclei (AGN)
  obtain very distant sources (redshift ~1, ~5 billion light years)
  No parallax, no proper motion

- IAU formed in 1990s a working group on
  International Celestial Reference Frame (ICRF)

- ICRF-1 adopted by the IAU as on 1998 Jan 01.
II.A. Surveys: How are sources found? Positions?

1. **Single dish surveys:** A single radio telescope sweeps the sky to search for point-like sources. Example: Parkes-MIT-NRAO 4.8 GHz *(Griffith & Wright, 1993)*
   ~10 arcsec positions.

2. **Connected element array surveys:**
   - next step is interferometric connected arrays such as the Very Large Array or ATCA
   - Positions improved to 10s of milli-arcsec

   - **North:** Jodrell Bank VLA Survey (JVAS)
     http://adsabs.harvard.edu/abs/1992MNRAS.254..655P

   - **South:** ATCA 20-GHz (AT20G), 5890 sources, Southern hemisphere
     (Murphy et al, MRAS, 2010)
     http://www.atnf.csiro.au/research/AT20G/

3. **Final Survey stage:** VLBI gets ~milli-arcsec positions e.g
   - **North:** VLBA Calibrator Survey
     http://adsabs.harvard.edu/abs/2002ApJS..141...13B

   - **South:** LBA Calibrator Survey
     http://arxiv.org/abs/1012.2607
II.A. Surveys: milli-arcsec VLBI surveys

South:
LBA Cal Survey 1:
~1 mas accuracy
view from south pole


North:
VLBA Calibrator Survey
~2200 sources, ~1 mas
Hammer-Aitoff Projection

http://adsabs.harvard.edu/abs/2002ApJS..141...13B

C.S. Jacobs 5 Mar 2013

212 “Defining” sources which define the orientation of the frame’s axes. Weak in the south.

“Candidate” sources (left) Plus a few “other” sources For a total of 608 sources.
Current Status of
Celestial Reference Frames
at radio wavelengths:

S/X ICRF2: 3.6cm, 8 GHz
K-band: 1.2cm, 24 GHz
X/Ka-band: 9mm, 32 GHz
ICRF-2 S/X 3.6cm: 3414 sources

40 μas floor. ~1200 obj. well observed, ~2000 survey session only

Credit: Ma et al, eds. Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009
295 “best” sources Define the orientation of the axes. Weak in the South

Credit: Ma et al, eds. Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009
K-band 1.2cm: 278 Sources

VLBA all northern, poor below Dec. -30°. $\Delta$Dec vs. Dec tilt= 500 $\mu$as

Lack of direct dual-band ion calibrations and lack of any station in south leads to poor ΔDec vs. Dec zonal stability: 500 μas tilt.

K(1.2cm) Declinations vs. S/X ICRF2 (current IAU standard)

Credit: K(1.2cm): Lanyi et al, AJ, 139,5, 2010
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, IERS, Germany, 2009
Cal. to Madrid, Cal. to Australia. Weakens south of Dec = -15deg

Credit: Jacobs et al, ISSFD, Pasadena, 2012
X/Ka Dec results: 482 Sources

Cal. to Madrid, Cal. to Australia. **Weakens southward. No ΔDec tilt**

Credit: Jacobs et al, ISSFD, Pasadena, 2012
Dual-band ion Calibrations and Station in south Leads to better $\Delta$Dec vs. Dec Zonal stability:

108 +/- 90 $\mu$as tilt

X/Ka(9mm) Dec. vs. S/X ICRF2 (current IAU standard)

S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, IERS, Germany, 2009
Planetary Ephemeris to ICRF Frame Tie

- ΔVLBI measurements of spacecraft around a planet obtains position in the ICRF frame

- Doppler and range measures spacecraft in planet center Frame.

Folkner et al, IAU. 2012
200 μas (1. nrad) residuals

Overview

I. Concepts and Background:
   A. What is a Reference frame? Concepts, uses, desired properties
   B. Networks: The instruments used to build the frame
      ad hoc, VLBA, EVN, Global, DSN, LBA, AuScope, etc.
   C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.
      1. Precession, proper motion, nutation, parallax
      2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

II. Celestial Frames built using VLBI
   A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
   B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
   C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

III. The Path to the Future:
   A. Error Budgets: a tool for allocating resources for improvement
   B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
   C. ICRF-3: the next standard radio frame
   D. Gaia: an optical frame with high accuracy
Error Budget for Reference Frame VLBI

The Tall Tent Poles
ΔVLBI Error Budget

- Quasar SNR
- Spacecraft SNR
- Clock Instability
- Dispersive Phase
- Station Location
- Earth Orientation
- Systematic Trop
- Fluctuating Trop
- Ionosphere
- Solar Plasma
- Quasar Position
- RSS Total

Credit: ΔVLBI budget from J.S. Border
Overview

I. Concepts and Background:
   A. What is a Reference frame? Concepts, uses, desired properties
   B. Networks: The instruments used to build the frame
      - ad hoc, VLBA, EVN, Global, DSN, LBA, AuScope, etc.
   C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.
      1. Precession, proper motion, nutation, parallax
      2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

II. Celestial Frames built using VLBI
   A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
   B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
   C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

III. The Path to the Future:
   A. Error Budgets: a tool for allocating resources for improvement
   B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
   C. ICRF-3: the next standard radio frame
   D. Gaia: an optical frame with high accuracy
X/Ka RA results: 482 Sources

Cal. to Madrid, Cal. to Australia. **Weakens south of Dec = -15deg**

Credit: Jacobs et al, ISSFD, Pasadena, 2012
Cal. to Madrid, Cal. to Australia. Weakens southward. No $\Delta$Dec tilt
Focus Work on the Tall Tent Poles

Systems Analysis shows dominant Errors are

- **Limited SNR/sensitivity**
  - already increasing bit rates: 112 to 448 Mbps. Soon to 2048?
- **Instrumentation**: already building better hardware
  - BWG phase calibrators, Digital baseband conversion & filters
- **Troposphere**: better calibrations being explored

- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 1 nrad (200 μas) level
  - Need observations below Declination of -45 Deg!
  - DSN at X/Ka has only Canberra, Australia (DSS 34)
  - Need 2nd site in the Southern hemisphere especially for upcoming southern ecliptic missions.
Attacking the Error budget

• SNR can be improved +6 to 9 dB!

• Instrumentation:
  Phase calibration with test signals
  Digital Baseband Conversion & Filtering

• Troposphere cals: WVR

• Southern Geometry
Results have been limited by SNR

Solution:

1) More bits:
   4X operational
   16X R&D
     in ~6-12 months
Will yield +3-6 dB
SNR increase

2) Ka pointing

Now with improved
Pointing calibrations
~3 dB more SNR

Total vs. early passes
+6-9 dB SNR increase!

Results have been SNR limited for SNR < 15 dB
Phased implementation, testing

- Data rate: 43 passes @ 112 Mbps (X/Ka 56/56 Mbps)
  
  3 passes @ 224 Mbps (X/Ka 80/144) \( \sim 3X \)

  24 recent @ 448 Mbps (X/Ka 160/288) \( \sim 5X \)

  in 3-12 mo. @ 2048 Mbps (X/Ka 192/1856) \( \sim 32X \)

Total Ka improvement 56 to 1856 Mbps => 5-10 psec del. precision

Reduces SNR below troposphere with increased Ka sensitivity!
Thus SNR will longer be the tallest tent pole.

Example: Ka-band Antenna Pointing

White pts. Represent Non-detection

Note Northern concentration of non-detects

Later, we got independent confirmation from ACME automated bore sight system of 18 mdeg errors

Credit: M. Vasquez, G. Baines, D. Rochblatt, C. Jacobs, C. Snedeker
Attacking the Error budget

- SNR can be improved +8 dB!

- **Instrumentation:**
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering

- Troposphere cals: WVR

- Southern Geometry
Results limited by No BWG Phase cal

Problem:
180 psec
~diurnal effect

Solution:
Ka-band Phasecal Prototype Demo’d
--- > Units being Built. Operations in ~1 year

Credit: C. Jacobs, B. Tucker, L. Skjerve
BWG Phase Calibrator

• Concept: Tunnel diode
  Alan Rogers et al (Haystack)

• JPL prototype BWG phase cal:
  Hammel, Tucker, & Calhoun,
  JPL Progress Report, 2003
  

• Production units: Blake Tucker

Tunnel Diode Chip
0.055” diameter by
0.020” thick
Mounted on
0.119” diameter carrier
for solid grounding
Beam Wave Guide phase calibrator

Direct interface to K connector inside coaxial structure.

Credit: Blake Tucker

Pulse driver mounted as close as possible and fed through coaxial structure to minimize rise time and ringing.
Sample, Baseband convert, Filter, Record

IF select switch:
12 inputs allows multiple bands, multiple antennas

Command & Control

Sampler: 1280 MHz, 8-bit/sample

Mark-5C recorder

Copper to fiber, Digital filter, Format

Design: Navarro et al. Photo credit: Les White
# Summary of Instrumental Improvements

<table>
<thead>
<tr>
<th>Instrument</th>
<th>MkIV</th>
<th>DBE/Mk5-C</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters</td>
<td>Analog 7-pole</td>
<td>Digital FIR</td>
<td>removes phase ripple in channel</td>
</tr>
<tr>
<td></td>
<td>Butterworth</td>
<td>phase linear</td>
<td></td>
</tr>
<tr>
<td>Spanned bandwidth</td>
<td>360 MHz</td>
<td>500 MHz</td>
<td>1.4X improvement</td>
</tr>
<tr>
<td>Data rate @ start</td>
<td>112 Mbps</td>
<td></td>
<td>DSN SNR limited</td>
</tr>
<tr>
<td></td>
<td>@ max.</td>
<td></td>
<td>trop/inst. limited</td>
</tr>
<tr>
<td>Data rate @ start</td>
<td>2048 Mbps</td>
<td>trop/inst. limited</td>
<td></td>
</tr>
<tr>
<td></td>
<td>@ max.</td>
<td>4096 Mbps</td>
<td>6X sensitivity</td>
</tr>
<tr>
<td>Phase Cal: HEF/70m</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BWG</td>
<td>No</td>
<td>Yes</td>
<td>removes 100s of psec</td>
</tr>
</tbody>
</table>
Attacking the Error budget

• SNR can be improved +8 dB!

• Instrumentation:
  Phase calibration with test signals
  Digital Baseband Conversion & Filtering

• Troposphere cals: WVR

• Southern Geometry
Troposphere Solution 1: Better Estimation

- Modified Least Squares to account for observation correlations -- both temporal and spatial

- Use Kolmogorov frozen flow model of Treuhaft & Lanyi (Radio Sci. 1987)

- Model increases information available to the estimation process
  1) Reduces parameter biases
  2) Reduces parameter sigmas

- Validation: Currently improves agreement $X/Ka$ vs. $S/X$ catalogs by about 10% in Declinations.
  Expect $\sim 30\%$ after SNR & phase cal errors peeled away to reveal troposphere errors.
Calibrating Troposphere Turbulence

- JPL Advanced Water Vapor Radiometer
  ~ 1 deg beam better matches VLBI
  improved gain stability
  improved conversion of brightness
temperature to path delay

- Initial demos show 1mm accuracy
  Goldstone-Madrid 8000 km baseline
  using X/Ka phase delays
  *Jacobs et al, AAS Winter 2005.*
  *Bar Sever et al, IEEE, 2007.*

- A-WVRs deployed at Goldstone/Madrid
  Seeking funding for Tidbinbilla, Aus

- A-WVR not used yet for Operations
Attacking the Error budget

• SNR can be improved +8 dB!
• Instrumentation:
  Phase calibration with test signals
  Digital Baseband Conversion & Filtering
• Troposphere cals: WVR

• Southern Geometry
Need 2nd Station in South

- Almost no Ka sources meet the accuracy goal south of equator!

- No coverage of South polar cap (-45 to -90 Dec)

- DSN weakly covers southern Ecliptic: only one strong baseline as California-Spain is weak in south

<table>
<thead>
<tr>
<th>Declination 1-sigma</th>
<th>Orange</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
<th>Purple</th>
<th>White</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-0.5 nrad meets future $\Delta$DOR spec</td>
<td>0.5-1.0</td>
<td>current $\Delta$DOR spec</td>
<td>1.0-1.5</td>
<td>1.5-2.5</td>
<td>2.5-5.0</td>
</tr>
</tbody>
</table>
Southern Stations?

• ESA Deep Space Antennas (DSA-1, 2, 3)
  – Cebreros, Spain: duplicate geometry to DSN in Robledo
  – New Norcia/Perth, Australia (helps but only 3000km from DSN Tidbinbilla)
  – **Malargue, Argentina**: Ideal, online fall-2012, NASA-ESA collaboration
    • 35m, X/Ka-band, 9,500 km baseline
    • Dry desert site is good for Ka-band
    • HA-Dec coverage: Tidbinbilla to Malargue:

• Hart, South Africa
  – diameter 26m
    • Resurfaced in 2005 (0.5mm RMS) efficient to 22 GHz

Credit: www.esa.int/esaMI/Operations/SEMGSDSMTWE_0.html 71
DSS 34 to Malargue, Argentina (DSA-3)

Simulated Coverage:
Dec +10 deg to –90 deg
Simulation of Added Southern Station

Before Southern Data

- 50 real X/Ka sessions augmented by simulated data
  simulate 1000 group delays, SNR = 50
  ~9000 km baseline: Australia to S. America or S. Africa

- Completes Declination coverage: cap region -45 to -90 deg
  200 μas (1 nrad) precision in south polar cap,
  mid south 200-1000 μas, all with just a few days observing.

After

Declination Sigma
Orange: < 100 μas
Red: < 200
Green: < 300
Blue: < 500
Purple: < 1000
White: > 1000

C.S. Jacobs 5 Mar 2013
Malargüe: The Next X/Ka VLBI Station

X/Ka: ESA Deep Space Antenna DSA 03
• Malargüe, Argentina
• Fall-2012 NASA/ESA collaboration
• 35-m, X/Ka-band, 9,500 km baseline
  Argentina-Australia covers south polar cap
  Full sky coverage for X/Ka!!
• Argentina-California & Australia-California
  orthogonal baselines for mid-latitudes
• High (1.5km), dry desert site: good for Ka-band
• HA-Dec coverage: Tidbinbilla to Malargüe:

Malargüe, Argentina 35-meter as of 26 Sept. 2012
ESA Deep Space Antenna
X/Ka-band capable
ESA’s Argentina 35-meter antenna adds 3 baselines to DSN’s 2 baselines
- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina
Goldstone, CA to Madrid & Australia + Malargüe to Australia.
95 in south cap (dec<-45); 19 ICRF2 Defining; 2/3 of cap non-ICRF2
Goldstone, CA to Madrid & Australia + Malargüe to Australia.
Outline

I. Concepts and Background:
   A. What is a Reference frame? Concepts, uses, desired properties
   B. Networks: The instruments used to build the frame
      - ad hoc, VLBA, EVN, Global, DSN, LBA, AuScope, etc.
   C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.
      1. Precession, proper motion, nutation, parallax
      2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

II. Celestial Frames built using VLBI
   A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
   B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
   C. Higher frequency radio frames: K&Q (24 & 43GHz), XKa (32 GHz)

III. The Path to the Future:
   A. Error Budgets: a tool for allocating resources for improvement
   B. Next-generation geodetic VLBI: Ultra-wide 2-14 GHz
   B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
   **C. ICRF-3: the next standard radio frame**
   D. Gaia: the return of optical
3rd generation International Celestial Reference Frame

Assessment of needs for ICRF-3
1. VLBA Cal Survey is most (2/3) of ICRF-2
   but positions are 5X worse than rest of ICRF-2
2. ICRF-2 is weak in the south
3. High frequency frames
   Fewer sources, weak in the south

Goals:
1. Complete ICRF-3 by 2018
   in time for comparisons with Gaia optical frame
2. Competitive accuracy with Gaia ∼ 70 µas (1-sigma RA, Dec)
4. High frequency frames (K, XKa, Q?)
   Improve number, accuracy, and southern coverage

III.C. ICRF-3 Needs

Assessment of needs for ICRF-3

1. Uneven precision of current ICRF-2 VCS’s 2200 sources (2/3 of the ICRF-2) 
   VCS precision is typically 1000 μas or 5 times worse than the rest of ICRF2.

<table>
<thead>
<tr>
<th>ICRF-2 Item</th>
<th>VCS</th>
<th>non-VCS</th>
<th>factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_src</td>
<td>2197</td>
<td>1217</td>
<td>VCS 1.8X better</td>
</tr>
<tr>
<td>median sessions</td>
<td>1</td>
<td>13</td>
<td>VCS 13X worse</td>
</tr>
<tr>
<td>median observations</td>
<td>45</td>
<td>249</td>
<td>VCS 5.5X worse</td>
</tr>
<tr>
<td>median time span</td>
<td>0</td>
<td>13 years</td>
<td>VCS arbitrarily worse</td>
</tr>
<tr>
<td>median RA sigma</td>
<td>621</td>
<td>130 μas</td>
<td>VCS 4.8X worse</td>
</tr>
<tr>
<td>median Dec sigma</td>
<td>1136</td>
<td>194 μas</td>
<td>VCS 5.9X worse</td>
</tr>
</tbody>
</table>
III.C. ICRF-3 Needs

Assessment of needs for ICRF-3

2. Southern Hemisphere:
   VLBI in general and ICRF-2 specifically lacks southern observations
III.C. ICRF-3 Needs

K-band

3. High frequency frames a K (24 GHz), XKa (32 GHz), and Q (43 GHz) lacking in the south
   K-band: HartRAO to Tidbinbilla?
   XKa: Malargüe, Argentina to Tidbinbilla, Australia
Outline

I. Concepts and Background:
   A. What is a Reference frame? Concepts, uses, desired properties
   B. Networks: The instruments used to build the frame
      ad hoc, VLBA, EVN, Global, DSN, LBA, AuScope, etc.
   C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.
      1. Precession, proper motion, nutation, parallax
      2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

II. Celestial Frames built using VLBI
   A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
   B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
   C. Higher frequency radio frames: K&Q (24 & 43GHz), XKa (32 GHz)

III. The Path to the Future:
   A. Error Budgets: a tool for allocating resources for improvement
   B. Next-generation geodetic VLBI: Ultra-wide 2-14 GHz
   B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
   C. ICRF-3: the next standard radio frame
   D. Gaia: the return of optical
III.D. Gaia Optical Frame

Gaia-Optical vs. VLBI-radio:

Celestial Frame tie
and
Accuracy Verification
Gaia frame tie and accuracy verification

Gaia: $10^9$ stars
- 500,000 quasars $V < 20$
- 20,000 quasars $V < 18$
- radio loud 30-300+ mJy
  and
- optically bright: $V < 18$
  ~2000 quasars

- Accuracy
  70 $\mu$as @ $V = 18$
  25 $\mu$as @ $V = 16$

References:
Lindegren et al, IAU 248, 2008
http://adsabs.harvard.edu/abs/2008IAUS..248..217L

Mignard, IAU, JD-7, 2012

Launch in Fall 2013

Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html%subhead7
Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids
  - radio: synchrotron from jet
  - optical: synchrotron from jet? non-thermal ionization from corona? big blue bump from accretion disk?

- Instrumental errors both radio & optical

- Analysis errors

Credit: Wehrle et al, μas Science, Socorro, 2009
Positions differences from ‘core shift’

- wavelength dependent shift in radio centroid.
- **3.6cm to 9mm core shift:**
  100 μas in phase delay centroid?
  <<100 μas in group delay centroid? \((Porcas, AA, 505, 1, 2009)\)
- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better
Source Structure vs. Wavelength

S-band
2.3 GHz
13.6 cm

X-band
8.6 GHz
3.6 cm

K-band
24 GHz
1.2 cm

Q-band
43 GHz
0.7 cm

The sources become better

Ka-band
32 GHz
0.9 cm

Image credit: P. Charlot et al, AJ, 139, 5, 2010

C.S. Jacobs 5 Mar 2013
Median optical magnitude $V_{\text{med}} = 18.6$ magnitude (~110 obj. no data)

> 146 of 577 objects optically bright by Gaia standard ($V<18$)
Gaia Optical vs. X/Ka frame tie

- Simulated Gaia measurement errors (sigma RA, Dec) median sigmas ~ 100 μas per component

- VLBI XKa radio sigmas ~200 μas per component and improving

- Covariance calculation of 3-D rotational tie using current 9mm radio sigmas and simulated Gaia sigmas
  
  \[
  \begin{align*}
  R_x & \pm 14 \mu\text{as} \quad \text{<- Weak. Needs south polar VLBI (Dec < -45)} \\
  R_y & \pm 11 \mu\text{as} \\
  R_z & \pm 10 \mu\text{as}
  \end{align*}
  \]

- Now limited by radio sigmas for which 2-3X improvement possible. Potential for rotation sigmas ~5 μas per frame tie component
Conclusions

I. Concepts and Background:
   A. Desire nonrotating, non-accelerating frame. Use a quasi-inertial with some accelerations
   B. Networks: The instruments used to build the frame
      - ad hoc, VLBA, EVN, Global, DSN, LBA, AuScope, etc.
   C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.
      1. Precession, proper motion, nutation, parallax
      2. Invention of radio astronomy. VLBI’s pursuit of sub-milli-arsecond accuracy.

II. Celestial Frames built using VLBI
   A. Surveys: Single dish,
      - connected arrays: Jodrells VLA (JVAS, north), ATCA 20 GHz (AT20G, south)
   B. VLBI ~mas:
      - VLBA Cal Survey (north), LBA Cal Survey (south)
   C. ICRF-1 (1998): The IAU moves to from optical (stars) to 212 Defining quasars.
      - ICRF-2 (2009) : 295 defining sources, 3414 total, 40 μas systematic floor
   C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

III. The Path to the Future:
   A. Error Budgets: a tool for allocating resources for improvement
   B. Case study: Improved X/Ka Frame: SNR, Instrumentation, Troposphere, Geometry
   C. ICRF-3 goals: 2018, improve south, improve VCS, improve K & X/Ka
   D. Gaia: 2021 the return of optical, 500,000 quasars, ~billion total sources
Y yo, minimo ser,
ebrio del gran vacío constelado,
a semejanza, a imagen del misterio,
me sentí parte pura del abismo,
rodé con las estrellas,
mi corazón se desató en el viento.
- Pablo Neruda

And I, infinitesimal being,
inebriated on the great starry void,
likeness, image of mystery,
I felt myself a pure part of the abyss,
I rode with the stars,
my heart broke free onto the open sky.
Estrellas, que rodean, señas,
Ojos, mis ojos captan la luz,
suave palpitar de mi corazón,
levado en alto por la brisa
vuelo de mi alma,
libre, nacida de nuevo
bajo un cielo maravilloso.

-C.S. Jacobs
(inspirado en un verso de Abraham Kron)