Developments in Expanding the Event Horizon Telescope: Phased ALMA and South Pole Telescope

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on behalf of European and Korean (sub)mm-VLBI

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What is the South Pole Telescope?
The South Pole Telescope

A 10m dish for CMB mapping
• Operated by University of Chicago

Recent VLBI capability
• PI is Dan Marrone at University of Arizona
• $700k NSF grant 2012-2015 for upgrade
• VLBI system with R2DBE, Mark6, maser, ...
• Dual-band EHT receiver by UArizona
  - ALMA mixers, 230 GHz + 345 GHz
  - fixed 1st LO (221.10 GHz, LSB)
  - diagnostic spectrometers
• Position, by SPT VLBI Team
  Lat  -89.9899996°
  Lon  -44.8727509°
  Alt   2843.5m
  (position of GPS antenna, within ~15m of VLBI)
(sub)mm-VLBI?
Science Drivers of (sub)mm-VLBI

Fine scale structure related to black hole/disk/jet systems
M 87, BL Lac, NGC 1052, ...

Accretion and structure at event horizon scales
Sgr A*, M 87

... objects scatter-broadened or self-absorbed at longer wavelengths

Galactic center pulsars

Image credit Astronomy/Roen Kelly
Requirements

High resolution to resolve expected structure
past progress
2003 IRAM 30m–ARO SMT 230 GHz : ~30 μas
2007 EHT ARO SMT–CARMA–SMA/JCMT : ~60 μas

Sensitivity of some mJy (Δt≈1h, BW≈2 GHz)
need SMA/JCMT, CARMA, ALMA

Sufficient uv coverage for imaging, modelfit
requires many stations: ARO SMT, SMA, JCMT,
APEX, LMT, PdBi/NOEMA, IRAM 30m, CARMA, ...
230 GHz VLBI Stations
March 2015 EHT

- DARMA
  Combined Array for Research in Millimeter-Wave Astronomy
  Cedar Flat, Calif.

- S.M.T.
  Submillimeter Telescope
  Mount Graham, Ariz.

- J.C. M.T. AND S.M.A.
  James Clerk Maxwell Telescope and Submillimeter Array
  Mauna Kea, Hawaii

- L.M.T.
  Large Millimeter Telescope
  Volcan Sierra Negra, Mexico

- APEX
  Atacama Pathfinder Experiment
  Llano Chajnantor, Chile

- 30-meter telescope
  Pico Veleta, Spain

Approximate distances:
- ~25-35 μas, ~8 Gλ
- ~35-50 μas
- ~28 μas, 7.2 Gλ
230 GHz VLBI Stations
Future EHT

- S.M.T. Submillimeter Telescope
  Mount Graham, Ariz.
- J.C.M.T. AND S.M.A.
  James Clerk Maxwell Telescope and Submillimeter Array
  Mauna Kea, Hawaii
- L.M.T.
  Large Millimeter Telescope
  Volcan Sierra Negra, Mexico
- APEX + ALMA
  Atacama Pathfinder Experiment
  Llano Chajnantor, Chile
- S.P.T.
  South Pole Telescope
  Amundsen–Scott South Pole Station, Antarctica
  (The South Pole Telescope was not part of the experiment in March 2015.)

Others:
- upgrading (PdBi/NOEMA)
- in progress (GLT, SPART)
- planned (CSO, Effelsberg)

Why add South Pole Telescope and ALMA?
Coverage on Sgr A* and M 87 (out of many other AGN science targets!)

If SPT and ALMA/APEX added to the mm-VLBI network
with ARO-SMT, SMA/JCMT, LMT, IRAM 30m, PdBi

Sgr A* uv coverage

M 87 uv coverage

Source elevation 24h
Coverage on Sgr A* and M 87

If SPT and ALMA/APEX added to the mm-VLBI network
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Sgr A* uv coverage

Variance in Sgr A* crescent model images

Red: uv plane regions where crescent models differ the most.

Kamruddin & Dexter (2013)
Coverage on Sgr A* and M 87
If SPT and ALMA/APEX added to the mm-VLBI network
with ARO-SMT, SMA/JCMT, LMT, IRAM 30m, PdBi

Sgr A* uv coverage

[Diagram showing Sgr A* uv coverage with SPT, ALMA/APEX, ARO-SMT, SMA/JCMT, LMT, IRAM 30m, PdBi]
Adding the South Pole Telescope and ALMA...
January 2015 Fringe Test at 230 GHz

13 January : Chile : Phased ALMA + ALMA OSF dish + APEX

12m APEX by MPIfR-OSO-ESO (VLBI PI: Zensus et al.)
Station with VLBI since 2012, cf. Roy et al. EVN 2013, Wagner et al. 2015

Phased ALMA >70m thanks to APP (VLBI PI: S. Doeleman)
During technical time. Phased array occasionally worse than single dish.

17 January : Intercontinental : SPT + APEX

10m SPT by UChicago (VLBI PI: D. Marrone)
Access to South Pole challenging. Last-minute receiver installation, VLBI setup.
First Light of SPT VLBI Receiver

D. Marrone, 16 January 2015, sent by rare satellite link
Map of 215 GHz emission in 30’ region around Sgr B2

+ Chris Kendall, Jason Soohoo and John Carlstrom
“Frequency Calibrators”? 

Confusing mix in EHT telescope VLBI tuneability, sub-band configurations

<table>
<thead>
<tr>
<th>Station</th>
<th>Tuning</th>
<th>Backend sub-bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT</td>
<td>1\textsuperscript{st} LO fixed, 2\textsuperscript{nd} LO 1 GHz steps, LSB</td>
<td>2 x 2048 MHz with R2DBE</td>
</tr>
<tr>
<td>ALMA</td>
<td>Semi-flexible, overlapping quadrants, LSB/USB</td>
<td>4 x 16 x 62.5 MHz or variations of it</td>
</tr>
<tr>
<td>APEX</td>
<td>1\textsuperscript{st} LO tunable (x12), 2\textsuperscript{nd} LO 1 MHz steps, USB</td>
<td>1 x 2048 MHz with R2DBE, 2 x 16x64 MHz with 1\textsuperscript{st} channel offset -32 MHz, or 2 x 16x62.5 MHz (&quot;ALMA mode&quot;) with 1\textsuperscript{st} offset -31.25 MHz with DBBC2</td>
</tr>
<tr>
<td>ARO SMT</td>
<td>1\textsuperscript{st} LO tunable (x3), USB/LSB</td>
<td>2 x 2048 MHz with R2DBE</td>
</tr>
<tr>
<td>IRAM 30m</td>
<td>1\textsuperscript{st} LO semi-flexible, risky, e.g. 24 kHz offset, ..</td>
<td>2 x 16x32 MHz 1\textsuperscript{st} channel offset -16.5 MHz</td>
</tr>
<tr>
<td>....</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

→ New untested VLBI observing modes that accommodate all stations : risky! Station recordings at which on-sky frequency? Sideband? Sub-band? Nyquist zone?
Mini-Survey for “Frequency Calibrators” at 215 GHz

Selected known 86 GHz SiO masers visible to SPT
Two detected with APEX at 215 GHz:

<table>
<thead>
<tr>
<th>Source</th>
<th>RA</th>
<th>Dec (J200)</th>
<th>$T'_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R Dor</td>
<td>4:36:45.61</td>
<td>-62:04:37.9</td>
<td>&lt; 1.0K</td>
</tr>
<tr>
<td>W Hya</td>
<td>13:49:01.92</td>
<td>-28:22:30.36</td>
<td>0.9 K (215 GHz SiO)</td>
</tr>
<tr>
<td>Orion KL</td>
<td>5:35:14.50</td>
<td>-5:22:29.60</td>
<td>3.0 K (215.2 GHz SO)</td>
</tr>
<tr>
<td>L2 Pupp</td>
<td>7:13:32.30</td>
<td>-44:38:22.92</td>
<td>&lt; 0.8 K</td>
</tr>
<tr>
<td>VY CMa</td>
<td>7:22:58.33</td>
<td>-25:46:03.24</td>
<td>&lt; 0.8 K</td>
</tr>
<tr>
<td>RW Vel</td>
<td>9:20:19.43</td>
<td>-49:31:30.72</td>
<td>&lt; 1.5 K</td>
</tr>
<tr>
<td>LP Hya</td>
<td>9:25:51.20</td>
<td>-24:00:37.80</td>
<td>&lt; 0.6 K</td>
</tr>
<tr>
<td>IW Hya</td>
<td>9:45:15.16</td>
<td>-22:01:44.76</td>
<td>&lt; 1.0 K</td>
</tr>
<tr>
<td>V Ant</td>
<td>10:21:09.00</td>
<td>-34:47:18.60</td>
<td>&lt; 1.0 K</td>
</tr>
<tr>
<td>X Cen</td>
<td>11:49:11.64</td>
<td>-41:45:27.36</td>
<td>&lt; 1.0 K</td>
</tr>
</tbody>
</table>

Notes. APEX gain is 0.015 K Jy$^{-1}$. Spectrometer velocity coverage ±2500 km s$^{-1}$ and 20 s integration. $T'_a$ upper limits are 3σ. R Dor detection in 217 GHz SiO is out of SPT tuning range. The Orion KL line at 215.2 GHz is likely SO (cf. Sutton et al. 1985). PRELIMINARY.
First VLBI Fringes!

Memos in progress for ALMA (G. Crew) and SPT (D. Marrone) ...

ALMA phasing efficiency of >99%, see V. Fish [1]

[1] Workshop on mm-VLBI with ALMA, January 2015, Bologna, Italy
Progress Towards 345 GHz VLBI

• First test: 1 Apr 2015 with 3C 279

APEX + Pico Veleta + ARO-SMT
9.9 Gλ, ~21 μas E-W
In progress at MPIfR Bonn, no fringes, yet...

• Soon: 28 Jul - 3 Aug 2015 “ALMA EHT Evaluation” likely 3C 454.3

345 GHz ALMA + APEX + SMA
10.9 Gλ, ~19 μas N-S
in addition to main

230 GHz ALMA + APEX + SMA + JCMT
7.2 Gλ, ~28 μas N-S

86 GHz ALMA + VLBA (+ Effelsberg)
2.5 Gλ, ~84 μas N-S
Summary

• Strong commissioning efforts by SPT and ALMA Phasing Project teams
  ➔ Got Fringes

• Fingers crossed for 345 GHz VLBI fringe tests success this month

• In 2016 finally 230(/345) GHz science VLBI obs. including ALMA, SPT?
Thank You
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