The Global Millimeter VLBI Array:
The central regions of Active Galactic Nuclei and the Origin of Jets

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(on behalf of the GMVA team)

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GMVA:
IRAM: M. Bremer, A. Grosz, M. Ruiz, S. Sanchez, C. Thum, et al.
NRAO-VLBA: V. Dhawan, C. Walker, et al.

Scientific Contributions/Collaborations:
KVN: S.S. Lee, B.W. Sohn, et al.
MIT-Haystack: S. Doeleman, V. Fish, et al.
FGAMMA program: L. Fuhrmann, M. Angelakis, I. Nestoras, et al. (MPIfR)

special thanks for providing data or figures, partly prior to publication:
T. Savolainen (MPIfR), M. Gurwell (SMA), Boston group, Michigan group, Mojave team
Motivation for mm-VLBI: The Physical Origin of Jets

Broad-band Spectral Energy Distribution – Relation to source structure

Jet-disk coupling and imaging of Event Horizons near SMBHs
3C454.3 – Spectral Variability in Radio-Bands

- Complex spectral evolution
- Time-lags vary between flares
- mm-variability: high $T_B > 10^{11...12}$ K
- I. Pauliny-Toth's: "superluminal brightening"

Data: FGAMMA collaboration (Fuhrmann et al.)

Spectral variability most pronounced and fastest at mm-/submm $\lambda$ (turnover $\nu_{\text{max}} \sim 40\text{-}230$ GHz)

Variability timescales of days to months lead to sizes of $\sim 1\text{-}100$ $\mu$as (or $< 5\text{-}50$ milli-pc)

→ need mm-VLBI to monitor these regions!
What does VLBI at short millimeter wavelengths offer?

• Study compact galactic and extragalactic radio sources and their jets with an angular resolution of a few ten micro-arcseconds in early stages of their kinematic evolution.

• Image regions which are (self-) absorbed and therefore not observable at longer cm-wavelength (spectrum, radiation/energy transport, outburst – ejection relations from radio to $\gamma$ – rays, counter-jets + torus).

• Study of the region of jet formation with highest achievable resolution (size & shape of jet at its base, 3D curvature + transverse jet structure, kinematics, spectrum, polarization & B-field).

• For nearby SMBHs (SgrA*, M87) reach scales of $\leq \sim 10$ gravitational radii, image Event Horizon and regions where GR-effects become important (orbital motion in accretion disk, light-bending, relativistic precession, frame dragging + BH rotation, jet-disk coupling (GRMHD), jet nozzle).

For all of this we need a high as possible observing frequency and a small as possible observing beam. Global VLBI at $\geq 86$ GHz provides this.
The Global Millimeter VLBI Array (GMVA)

Imaging with ~40 μas resolution at 86 GHz

Baseline Sensitivity

in Europe:

30 – 300 mJy

in US:

100 – 300 mJy

transatlantic:

50 – 300 mJy

Array:

1 – 3 mJy / hr

(assume 7σ, 100 sec, 512 Mbps)

http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm

• Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m), planned: Yebes (40m)

• USA: 8 x VLBA (25m)

Proposal deadlines: February 1st, October 1st
• History of 3mm-VLBI

• 1981: first mm-VLBI experiments successful
• early 1990's: formation of the Coordinated Millimeter VLBI Array (CMVA) by Haystack observatory in conjunction with a number of mm-capable observatories
• throughout the 1990's: efforts to enhance and expand this collaboration e.g. provision of VLBI recorders and masers to IRAM by MPIfR, outfitting VLBA antennas with 3mm receivers
• 2002: disengagement of Haystack obs. and last CMVA session in Autumn 2002
• early 2003: MPIfR initiative to continue the facility, MoU between MPIfR, NRAO, IRAM, OSO and MRO for future, global VLBI at 3mm

→ new organisation: the Global mm VLBI Array (GMVA)

• September 2003: first GMVA Call for proposals, include phased PdB
• April 2004: first GMVA observations
• 2005: switch to MK5A disk recording, add dual polarisation
• 2007/2008: PdB upgrade (better phasing stability, new H-maser)
• 2009: new EMIR receiver at PV, better sensitivity
Current Operation of the GMVA

• Observing sessions
  • 2 sessions per year (spring/autumn), each up to 5 days duration (dates fixed 6-12 months in advance)

• Proposing for observations
  • proposal deadlines 1st February, 1st October, ‘Call for proposals’ 6 months in advance
  • information for astronomers wishing to use the GMVA is provided by a web page: http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm/index.html
  • proposal review by participating GMVA observatories following their own internal procedures. Results collated by the European GMVA Scheduler, a joint decision is made together with the VLBA scheduler regarding scheduling

• Observations
  • European and VLBA schedulers jointly agree a block schedule for each session
  • PI of proposals provide scheduling details of their observations in collab. with the Schedule Coordinator at MPIfR
  • Schedule Coordinator provides a final, integrated session schedule to the GMVA observatories (taking into account e.g. need for pointing checks, antenna calibration, etc.)
  • individual GMVA observatories perform the observations on behalf of the investigators with often MPIfR logistical and observing support and expertise at the IRAM sites
  • disk-based MK5 recording systems: recording rate of 512 Mb/s as default for all GMVA continuum observations
  • correlation at Bonn MK4 correlator; data conversion to UV-fits AIPS standard
Enhance 3mm global VLBI by including the 3 largest European high frequency-telescopes:

Effelsberg 100 m (MPIfR)

Plateau de Bure, 6 x 15 m (IRAM, France)

Pico Veleta 30 m (IRAM, Spain)

Baseline lengths (km):

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<tr>
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<tr>
<td>Pdb</td>
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fringe spacing: 0.4 – 1.1 mas,
sensitivity > 50 -90 mJy (7σ, 512 Mbps)
GMVA Proposal and Observation Statistics 2003 – 2010

• Proposals

• 15 proposal deadlines since October 2003 with a total of 61 submitted proposals (including Oct. 2010), many for multi-epoch monitoring covering several sessions
• dual polarisation requested now in most proposals, spectral line (SiO masers) in 1 proposal, often strong and compact (famous) AGNs for up to 6 epochs (e.g. 3C84, 3C454.3, BL Lac, OJ287, NRAO150), γ-ray sources (Fermi, Boston, Bologna)
• 20 out of the 61 so far reviewed proposals rejected, 5 approved for partial observation
• 4 MPIfR-IRAM add hoc observations, ToOs

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<td>October 2010</td>
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<td><strong>Sum</strong></td>
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<td><strong>20,55</strong></td>
<td><strong>136</strong></td>
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Detailed Proposal and Observation statistics:

about 70% of the proposals make it on the sky
GMVA Proposals by Nationality 2004-2010

64 scientists from 10 different countries

GMVA – Proposal statistics

Observed experiments: 87 about 50% multi-epoch

Observing Sessions

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Projects:
- PR. China
- Finland
- France
- Germany
- Ireland
- Italy
- S. Korea
- Spain
- UK
- USA
Why is mm-VLBI still non-standard and requires special care?

- variable weather, non optimum observing conditions, limited scheduling flexibility
- phase fluctuations and short atmospheric coherence time (< 20s)
- limitations at telescopes (pointing, focusing, gain curves, low $\eta_A$, etc.)
- limited bandwidth, low SNR in 8-16 MHz wide IFs (frequency synthesis)
- alignment of IFs (man. phasecal problem)

Solution:

better control of telescope gain, larger bandwidth+DBEs, more mm-telescopes
phase correction (WVR), improved analysis software (eg. fringe fitting),
AND more accurate:

    calibration, calibration, calibration, ....

Important: mm-VLBI relies on ampl. self-cal, works well only for N > 10 antennas!
Highlights from recent 3mm-VLBI with the GMVA

- stratified + helical jets (3C345, 3C273)
  - e.g. Qian et al. 2009 (RAA)

- 3mm AGN survey
  - (127 sources)
  - Lee et al. 2008 (AJ)

- precessing jet nozzle (NRAO150)
  - Agudo et al. 2007 (A&A)

- obscured counter-jet (Cygnus A)
  - Krichbaum et al. 2008
Results from the new 3mm VLBI survey (127 sources):

\[
T_b = \frac{2 \ln 2}{\pi k_B} \frac{S_{\text{tot}} \lambda^2}{d^2} (1 + z)
\]

Brightness temperature decreasing with frequency?

Brightness temperature increasing along jet; accelerating jets?

A larger mm-VLBI AGN survey is needed!
Size of jet base appears too small for magnetic sling-shot acceleration. Direct relation to BH more likely → a GR-MHD Dynamo?

Limit of the size of the jet base (uniform weighting):

\[ 197 \times 54 \ \mu \text{as} = 21 \times 6 \ \text{light days} = \frac{54}{15} R_s \]

transverse width of jet at 0.5 mas: \(~140 \ R_s\)
BP versus BZ mechanism

Blandford – Payne mechanism:
centrifugal acceleration in magnetized accretion disk wind

Blandford – Znajek mechanism:
electromagnetic extraction of rotational energy from Kerr BH

discriminate via
Jet speed
Jet width
Shape of Nozzle
Jet structure
etc.

need to reach scale of $\sim 1 \times 10^3 R_G$
New:
Global 7mm VLBI maps of Cyg A
(EVN, VLA, VLBA, GBT)

First 43 GHz image from DivX Software Correlator

jet acceleration from 0.1c – 0.7c

U. Bach et al. 2008
Detection of the counter-jet of Cygnus A at 43 and 86 GHz

86 GHz  2005.791  GMVA

beam: 140 x 56 μas
0.15 x 0.06 pc

43 GHz  2007.807  Global VLBI

gap between jet and counter jet at 43 GHz: ≈ 0.5 mas ~ 2200 Rₜₚ
at 86 GHz: ≤ 0.2 mas ≤ 880 Rₜₚ
New: Intrinsic Jet-to-Counterjet Ratio determined from 3mm-VLBI

$R_{86\ GHz} = 1.32 \pm 0.12$

Parameters of torus:
inner edge: 0.3 mas (0.3 pc)
outer edge: 4-5 mas (4-5 pc)

Krichbaum et al. 2008
86 GHz GMVA images of 3C84: jet base resolved!

VSOP 5 GHz
Aug 2001

Clean LL map. Array: ESSpyFmmXvFrIbrkPMHua
3C84 at 86.199 GHz 2008 May 09

GMVA 86 GHz
May 2008

Clean LL map. Array: ESSpyFmmXvFrIbrkPMHua
3C84 at 86.199 GHz 2008 May 09

Nuclear region and sub-mas jet base resolved: 42 μas corresponding to a linear scale of 16 lightdays or 142 R_S in units of the central SMBH → huge potential for future studies!

data:
M.J. Kim, S.S. Lee et al. 2010 and in prep.
FERMI-LAT: Gamma-ray lightcurve of 3C454.3

Data: gamma-ray variability from public Fermi website
+ Dermer et al. 2010, Ackermann et al. 2010

$t_{\text{var}} \sim 1$ day at peak

$\delta > 13 \; (\Gamma \sim 20)$

$R < 0.2 \; (\Gamma/20)^2 \; (t_{\text{var}}/1\text{day}) \; \text{pc} < 26 \mu\text{as}!!$

MJD: 55112: this GMVA obs.

Super-resolution 75%

27 $\mu$as beam

Origin of inter-day $\gamma$-ray variability within unresolved mm-VLBI core?
3C454.3 – Quasi-simultaneous VLBI images at 7mm and 3mm

identical beam: 0.15 x 0.05 mas

two inner jet components at $r \sim 0.08$ and 0.15 mas (0.6 / 1.2 pc)

Jorstad 2010: expected position K3 ($T_0=2007.93, \mu=0.09$ mas/yr) $\rightarrow r = 0.17\pm0.05$ mas
Faint jet seen at 15 GHz (VLBA) is also detected at 86 GHz in a strongly uv-tapered GMVA image! The imaging sensitivity of the GMVA will further improve with MK5C.
OJ 287 in October 2009: comparison of inner structure

43 GHz VLBA & 86 GHz GMVA image both show a jet extending 0.4 mas (1.8 pc) south. It is misaligned by about 90 deg relative to the mas-scale jet!
OJ 287 in October 2009: Spectrum of inner jet

86 GHz 2009 Oct 09

Is this the core?

modelfit: 0.21 x 0.043 mas beam

quasi simultaneous radio spectrum from FGAMMA program

VLBI component spectra from 15 + 43 + 86 GHz
Quality of VLBA images – The jet of 3C273

8 VLBA stations (no 3mm at SC and HN)  6 VLBA stations (KP and LA removed)

Dramatic loss (2.5) in image fidelity and sensitivity if the "wrong" VLBA stations would be removed!

Oct. 27, 2010

Peak: 2258 mJy; rms: 3.4 mJy
Dynamical range: 664

Peak: 1720 mJy; rms: 6.3 mJy
Dynamical range: 273

data:T. Savolainen et al.
Angular and Spatial Resolution of mm-VLBI

<table>
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<th>( \lambda )</th>
<th>( \nu )</th>
<th>( \theta )</th>
<th>( z=1 )</th>
<th>( z=0.01 )</th>
<th>( d=8 \text{ kpc} )</th>
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<tr>
<td>3 mm</td>
<td>86 GHz</td>
<td>45 ( \mu \text{as} )</td>
<td>0.36 pc</td>
<td>9.1 mpc</td>
<td>1.75 ( \mu \text{pc} )</td>
</tr>
<tr>
<td>2 mm</td>
<td>150 GHz</td>
<td>26 ( \mu \text{as} )</td>
<td>0.21 pc</td>
<td>5.3 mpc</td>
<td>1.01 ( \mu \text{pc} )</td>
</tr>
<tr>
<td>1.3 mm</td>
<td>230 GHz</td>
<td>17 ( \mu \text{as} )</td>
<td>0.14 pc</td>
<td>3.4 mpc</td>
<td>0.66 ( \mu \text{pc} )</td>
</tr>
<tr>
<td>0.87 mm</td>
<td>345 GHz</td>
<td>11 ( \mu \text{as} )</td>
<td>0.09 pc</td>
<td>2.2 mpc</td>
<td>0.43 ( \mu \text{pc} )</td>
</tr>
</tbody>
</table>

linear size: \(~10^3 R_s^{9} ~ 20-100 R_s^{9} ~ 1-5 R_s^{6}\)

for nearby sources, these scales correspond to 1 – 100 Schwarzschild radii, depending on distance and black hole mass!

→ mm-VLBI can directly image (!) the vicinity of SMBHs (Event Horizon, BH-Shadow, GR-theory)!

→ best candidates: Sgr A* (10 \( \mu \text{as} = 1 R_s^{6} \)) and M 87 (Cen A is far south, M81 & NGC4258 are weak)

→ need sensitive mm-telescopes (ALMA) to image the emission around Black Holes in AGN

→ need both, European + US-telescopes to obtain optimum sensitivity and resolution.
Observing Black Holes with mm-VLBI using the phased ALMA

High speed jets ejected by Black Hole.

Disk of material spiraling into Black Hole.

The Black Hole: measure curved space time, mass and spin

Orbiting hot spot and light bending

Size found by 1mm VLBI observations

3.7 $R_S$

mJy sensitivity with ALMA

ALMA 50x12m

Image credits:
- NASA/CXS/M. Weiss
- Image: Broderick & Loeb 2006
Global 3mm VLBI: Future Sensitivities

- Adding European mm-telescopes to the VLBA improves the angular resolution by factor ~2 and imaging sensitivity by a factor of ~3.
- The addition of telescopes with large collecting area (GBT, LMT, CARMA, SRT, ...) will give another factor of 2-3.
- Addition of ALMA leads to mJy sensitivities and improves the overall sensitivity by a factor of 10, over present day values.
- Another factor of sqrt(rate/ 2Gbit/s) in sensitivity will be obtained via a further increase of observing bandwidth.

<table>
<thead>
<tr>
<th>Array</th>
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<tr>
<td>VLBA, 2 Gb/s</td>
<td>VLBA(8)</td>
<td>&gt; 164</td>
<td>2.33</td>
<td>1.0e03</td>
<td>no HN, no SC</td>
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<tr>
<td>GMVA, 2 Gb/s</td>
<td>VLBA+EB+PV+PB+ON+MH</td>
<td>&gt; 33</td>
<td>0.86</td>
<td>2.8e03</td>
<td>68 mJy VLBA-IRAM</td>
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<tr>
<td></td>
<td>+ Yb</td>
<td></td>
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<td>68 mJy VLBA-Yb</td>
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<tr>
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<td>present GMVA+Yebes</td>
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<td>+ LMT + GBT present</td>
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<td>&gt; 5</td>
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<td>12.9e03</td>
<td>5 mJy ALMA-GBT</td>
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</table>

assuming: 500 MHz bandwidth (2 Gbit/s), t=20 sec, 7sigma fringe detection, 2 bit sampling

- Adding European mm-telescopes to the VLBA improves the angular resolution by factor ~ 2 and imaging sensitivity by a factor of ~3.
- The addition of telescopes with large collecting area (GBT, LMT, CARMA, SRT, ...) will give another factor of 2-3.
- Addition of ALMA leads to mJy sensitivities and improves the overall sensitivity by a factor of 10, over present day values.
- Another factor of sqrt(rate/ 2Gbit/s) in sensitivity will be obtained via a further increase of observing bandwidth.
• 3mm VLBI imaging complements broad-band variability studies (SEDs) and is absolutely essential for the interpretation of results from satellite missions (e.g. PLANCK, FERMI, etc.).

• 3mm VLBI is needed to bridge the gap between cm-VLBI (up to 43 GHz) and planned submm-VLBI at 230/345 GHz (Event Horizon Telescope).

• Future addition of large apertures (ALMA, GBT, CARMA) will boost 3mm-VLBI to mJy sensitivities. (Note: 3mm VLBI helps to justify ALMA phasing effort.)

• Since the atmosphere limits the accuracy of the a-priori calibration, one needs a sufficiently large number of VLBI telescopes (> 10) to obtain reliable results from amplitude self-calibration.

• Because of the small observing beam and rapid structural variability of the sources, a much denser time sampling would be very desirable (>> 2 times per year).

⇒ The VLBA can and "should" play a major role in this.
END
EVN/Global VLBI: Image Sensitivities
(numbers in \( \mu \text{Jy/beam} \))

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<td>-</td>
<td>-</td>
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assumptions: 512 Mbit/s, single polarisation, 2 bit sampling, 60 min. on source
1 sigma thermal noise, natural weighting

Future aim: mm-VLBI should reach similar sensitivity/performance as global VLBI at cm-wavelengths!
→ add stations + increase observing bandwidth to Gbit/s rates
→ expect to reach < 100 \( \mu \text{Jy/beam} \) @ 86 GHz in 2011/12
(for 2 Gbit/s with MK5C)
**EVN/Global VLBI: Angular Resolution**
(numbers in milli-arcseconds)

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<td>VLBA</td>
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<td>4</td>
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<td>0.9</td>
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<td>GMVA</td>
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<td>-</td>
<td>-</td>
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spatial scale: for z =1 ($\Lambda$CDM cosmology), 1 mas = 8 pc

sub-pc scale resolution only for global VLBI at $\lambda \leq 3$mm!
large IRAM telescopes important for sensitivity across Atlantic!
ALMA will revolutionize mm-VLBI
## Global VLBI at 3mm: Existing and possible future antennas

<table>
<thead>
<tr>
<th>Station</th>
<th>Country</th>
<th>Diameter</th>
<th>Eff.Diameter</th>
<th>Zenith Tsys</th>
<th>Gain</th>
<th>App.Eff.</th>
<th>SEFD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[m]</td>
<td>[m]</td>
<td>[K]</td>
<td>[K/Jy]</td>
<td>[%]</td>
<td>[K]</td>
</tr>
<tr>
<td>Effelsberg</td>
<td>Germany</td>
<td>100</td>
<td>80</td>
<td>125</td>
<td>0,137</td>
<td>8</td>
<td>915</td>
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<td>Plateau de Bure</td>
<td>France</td>
<td>6x15</td>
<td>34,8</td>
<td>90</td>
<td>0,208</td>
<td>67</td>
<td>433</td>
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<tr>
<td>Pico Veleta</td>
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<td>30</td>
<td>90</td>
<td>0,141</td>
<td>55</td>
<td>639</td>
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<tr>
<td>Onsala</td>
<td>Sweden</td>
<td>20</td>
<td>20</td>
<td>250</td>
<td>0,051</td>
<td>45</td>
<td>4882</td>
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<tr>
<td>Metsähovi</td>
<td>Finland</td>
<td>14</td>
<td>14</td>
<td>250</td>
<td>0,017</td>
<td>30</td>
<td>14944</td>
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<tr>
<td>VLBA(8)</td>
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<td>25</td>
<td>25</td>
<td>100</td>
<td>0,034</td>
<td>19</td>
<td>2960</td>
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**future Europe**

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<th>Zenith Tsys</th>
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<tbody>
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<td>40</td>
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<tr>
<td>Noto</td>
<td>Italy</td>
<td>32</td>
<td>32</td>
<td>100</td>
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<td>64</td>
<td>100</td>
<td>0,350</td>
<td>30</td>
<td>286</td>
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</table>

**future America**

<table>
<thead>
<tr>
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<th>Eff.Diameter</th>
<th>Zenith Tsys</th>
<th>Gain</th>
<th>App.Eff.</th>
<th>SEFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBT</td>
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<td>100</td>
<td>100</td>
<td>0,996</td>
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<td>100</td>
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<tr>
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<td>100</td>
<td>0,140</td>
<td>50</td>
<td>713</td>
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<tr>
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<td>Mexico</td>
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<td>50</td>
<td>100</td>
<td>0,356</td>
<td>50</td>
<td>281</td>
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<tr>
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<td>Chile</td>
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<td>85</td>
<td>100</td>
<td>1,233</td>
<td>60</td>
<td>81</td>
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<tr>
<td>ALMA, single</td>
<td>Chile</td>
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<td>12</td>
<td>100</td>
<td>0,025</td>
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