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Multi-step VLBI observations of weak extragalactic radio sources to align the ICRF and the future Gaia frame

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CONTEXT

The International Celestial Reference Frame (ICRF) is the realization at radio wavelengths of the International Celestial Reference System (ICRS [1]), through Very Long Baseline Interferometry (VLBI) measurements of extragalactic radio source positions [2,3]. It was adopted by the International Astronomical Union (IAU) as the fundamental celestial reference frame during the IAU 23rd general assembly at Kyoto (Japan), in August 1997. The ICRF currently consists of a catalogue with the VLBI coordinates of 717 extragalactic radio sources (from which 212 are *defining* sources), with sub-milliarcsecond accuracy.

The European space astrometry mission Gaia, to be launched by 2011, will survey about (i) one billion stars in our Galaxy and throughout the Local Group, and (ii) 500 000 Quasi Stellar Objects (QSOs), down to an apparent optical magnitude V of 20 [4]. Optical positions with Gaia will be determined with an unprecedented accuracy, ranging from a few tens of microarcseconds (µas) at magnitude 15-18 to about 200 µas at magnitude 20. Unlike Hipparcos, Gaia will permit the realization of the extragalactic reference frame directly at optical bands, based on the QSOs that will have the most accurate positions (i.e. those with $V \leq 18$ [5]; probably ~10 000 of these QSOs [6]). A preliminary Gaia catalogue is expected to be available by 2015 with the final version by 2019.

In the future, aligning the ICRF and the Gaia celestial reference frame will be crucial for ensuring consistency between the measured radio and optical positions. This alignment, to be determined with the highest accuracy, requires several hundreds of common sources, with a uniform sky coverage and very accurate radio and optical positions. Obtaining such accurate positions implies that the link sources must have (i) an apparent optical magnitude V brighter than 18 (for the highest Gaia astrometric accuracy), and (ii) no extended VLBI structures (for the highest VLBI astrometric accuracy).

In a previous study, we investigated the current status of this alignment based on the present list of ICRF sources [7]. We found out that although about 30% of the ICRF sources have an optical counterpart with $V \leq 18$ (**Figure 1**), only one third of these are compact enough on VLBI scales for the highest astrometric accuracy (**Figure 2**).

Overall only 10% of the current ICRF sources (70 sources) are available today for the alignment with the future Gaia frame. This highlights the need to identify additional suitable radio sources, which is the purpose of the project described here.

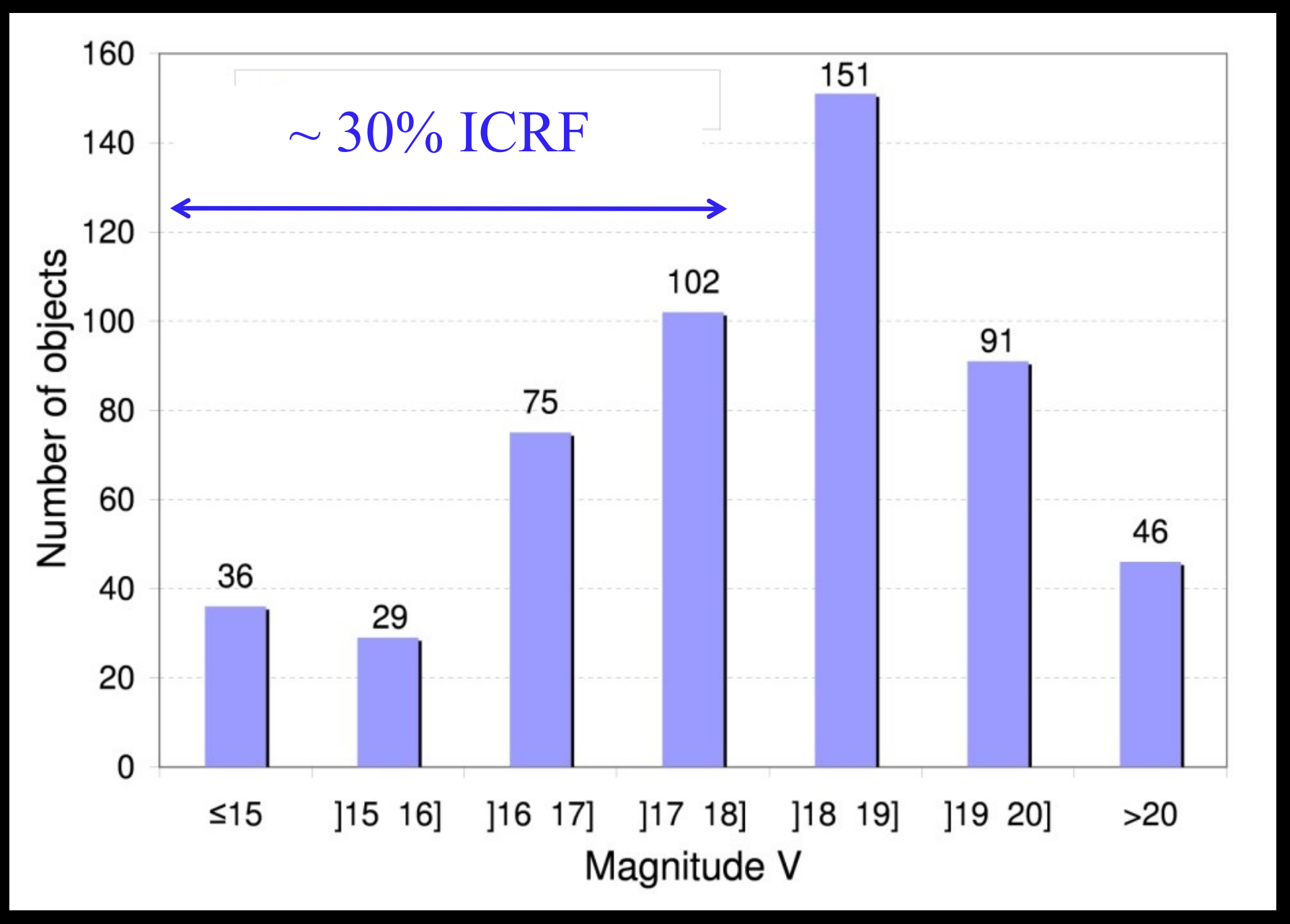


Figure 1: Optical apparent magnitude (V) distribution for the 530 ICRF sources with an optical counterpart in Véron & Véron (2006).

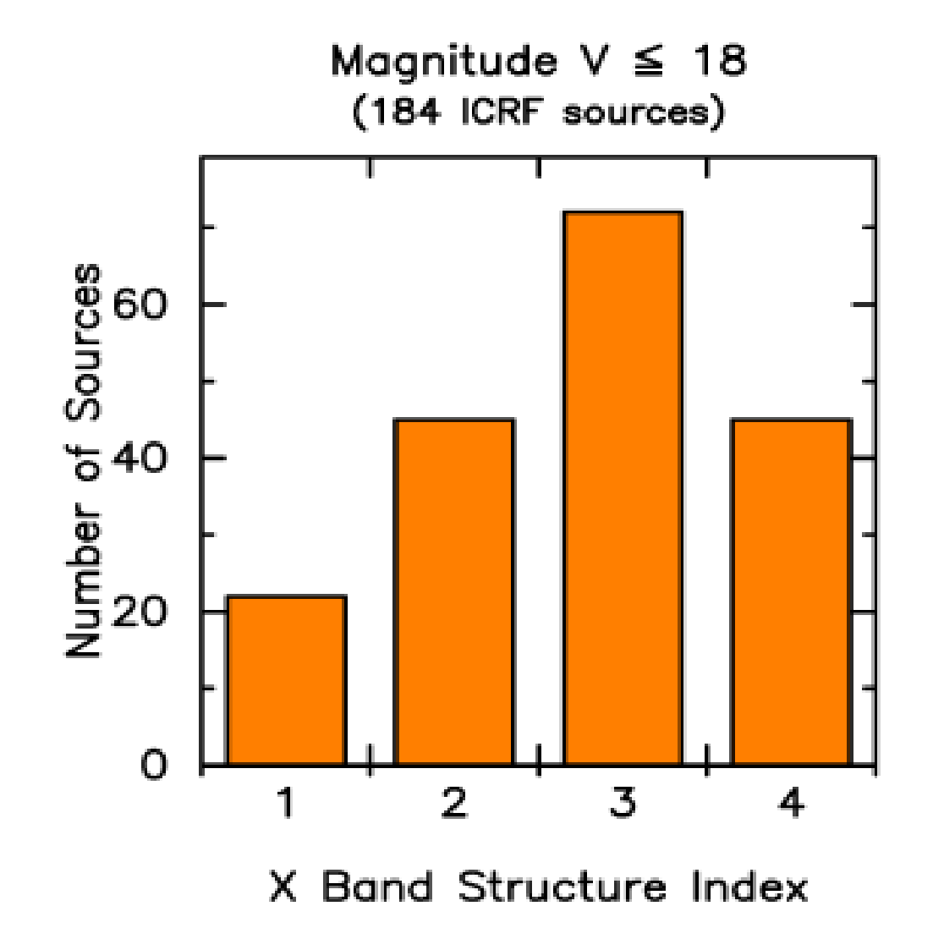
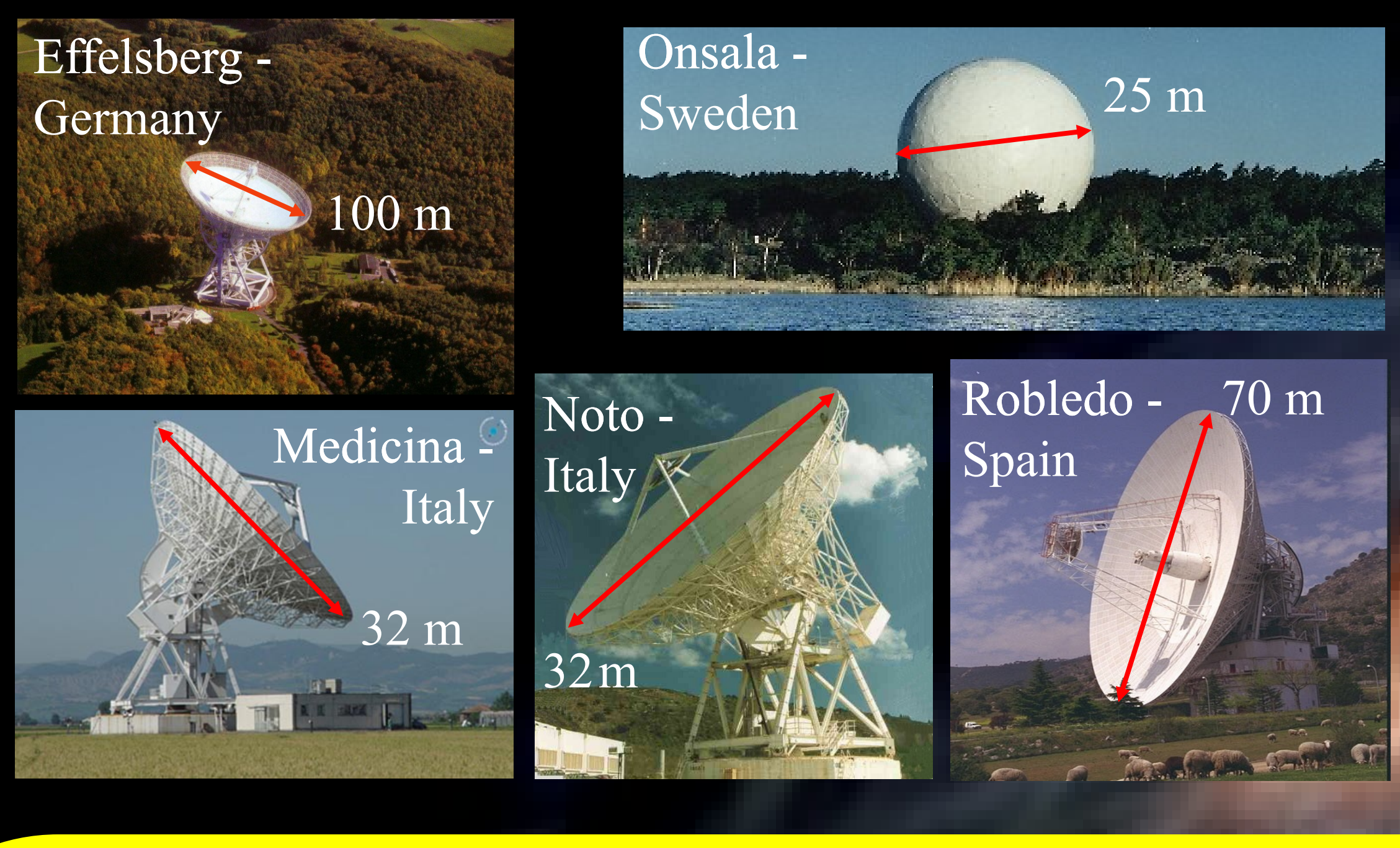


Figure 2: Structure index distribution for the 30% of ICRF sources with an optical counterpart such that $V \leq 18$. Structure index values of 1 or 2 point to the most compact sources with the highest astrometric quality (i.e. those suitable for the Gaia link), whereas larger values of the structure index (3 or 4) correspond to sources with extended structures (see [8,9] for details).

Figure 3: The EVN radio telescopes constituting the VLBI array used for observing ~450 weak extragalactic radio sources in EC025A and EC025B experiments (Effelsberg, Medicina, Noto, Onsala; and Robledo for part of the time in EC025B).



Strategy to identify new VLBI radio sources for the ICRF/Gaia alignment

Searching for additional radio sources suitable for aligning accurately the ICRF and the GAIA frame could rely on the VLBA Calibrator Survey (VCS; [10] and references therein), a catalogue of more than 3000 extragalactic radio sources observed with the VLBA (Very Long Baseline Array; the american VLBI network). This investigation is currently underway. Another possibility is to search for new VLBI sources, which implies going to weaker radio sources that have a flux density typically below 100 mJy. This can now be envisioned owing to the recent increase in the VLBI network sensitivity (i.e. recording now possible at 1Gb/s) and by using a network with big antennas like the EVN (European VLBI Network).

A sample of ~450 radio sources that have never been observed with VLBI (i.e. not part of ICRF or VCS) have been selected for this purpose by cross-identifying the NRAO VLA Sky Survey (NVSS [11]), a deep radio survey (complete to the 2.5 mJy level) that covers the entire sky north of -40º, with the Véron-Cetty and Véron (2006) optical catalogue of quasars and BL Lac objects [12]. This sample is based on the following criteria:

- $V \leq 18$ (for an accurate position with Gaia),
- $\delta \geq -10^{\circ}$ (for possible observing with northern VLBI arrays), and
- NVSS flux density $\geq$ 20 mJy (for possible VLBI detection).

The observing strategy to identify the appropriate link sources in the sample includes three successive steps:

(1) To determine the VLBI detectability of these weak radio sources, never observed before with VLBI;
(2) To image the sources detected in the previous step, in order to reveal their VLBI structure;
(3) To determine an accurate astrometric position for the most point-like sources of the sample.

VLBI results

Initial VLBI observations for this project were carried out in June and October 2007 (during two 48-hours experiments, named EC025A and EC025B, respectively), with a network of VLBI antennas described in **Figure 3**. The purpose of these two experiments was to determine the VLBI detectability of the 447 weak radio sources in our sample based on snapshot observations.

Our results indicate excellent detection rates of 97% at X band and 89% at S band. Overall, 398 sources were detected at both frequencies (see their distribution on the sky in **Figure 4**). This is in agreement with the detection rate reported in [13] (80%) for quasars from the Sloan Digital Sky Survey. **Figure 5** plots the overall mean correlated flux densities (i.e. for each source and band, the mean over all scans and baselines detected) at both bands:

- At X band, 432 sources were detected. The mean correlated fluxes range from 1 mJy to 190 mJy, with a median value of 26 mJy.
- At S band, 399 sources were detected. The mean correlated fluxes range from 8 mJy to 481 mJy, with a median value of 46 mJy.

A comparison between the X-band flux density distribution for our sources, those from the VCS and the ICRF shows that the sources of our sample are indeed much weaker. On average, they are 27 times weaker than the ICRF sources and 8 times weaker than the VCS sources (**Figure 6**).

The spectral index α was also investigated (see definition in **Figure 7**), and the sources with a compact core are expected to have $\alpha > -0.5$. The spectral index distribution is plotted in **Figure 7** for the 398 radio sources detected at both frequencies in EC025A and EC025B. The median value of α is −0.34 and about 70% of the sources have $\alpha > -0.5$, hence indicating that they must have a dominating core component, which is very promising for the future stages of this project.

The next step will be targeted at imaging most of the 398 sources that we have detected at both frequencies, by using the global VLBI network (EVN+VLBA), in order to identify the most point-like sources and therefore the most suitable ones for the ICRF−GAIA link.

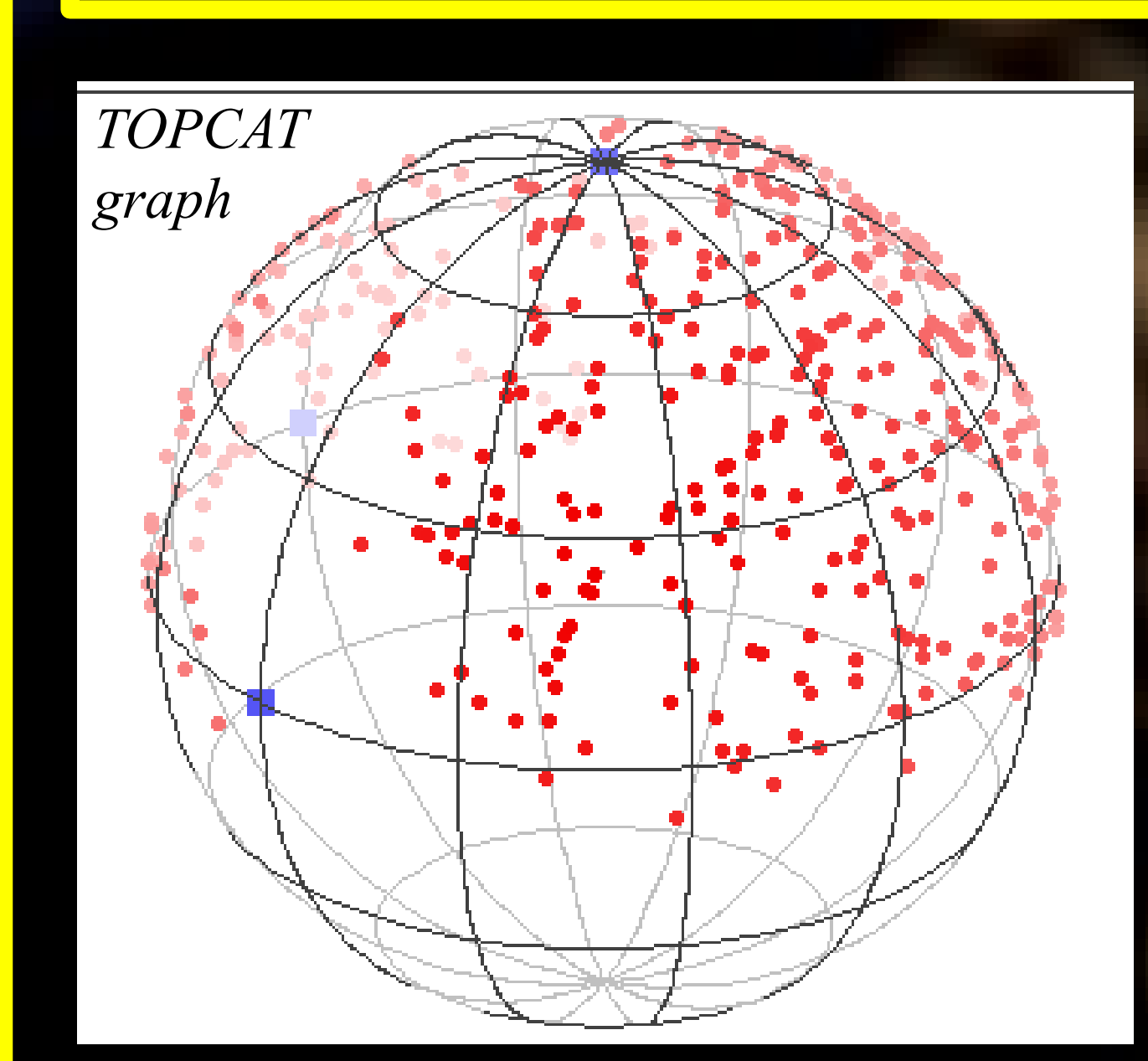


Figure 4: Sky distribution for the 398 weak radio sources detected with the EVN, during EC025A and EC025B.

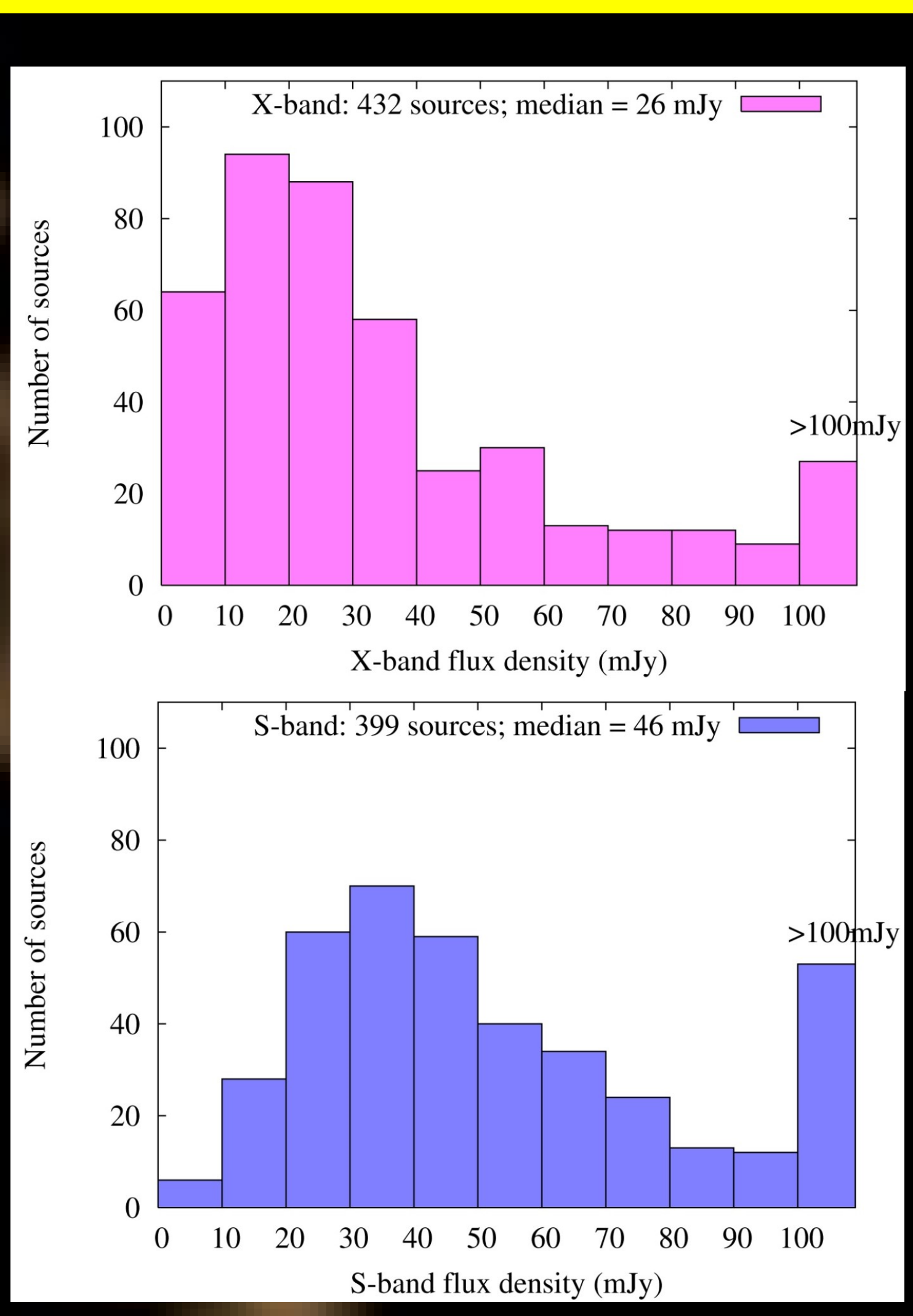


Figure 5: Flux density distribution for the sources detected in EC025A and EC025B experiments. Upper panel: X-band flux density (8.4 GHz, 3.6 cm); Lower panel: S-band flux density (2.3 GHz, 13 cm).

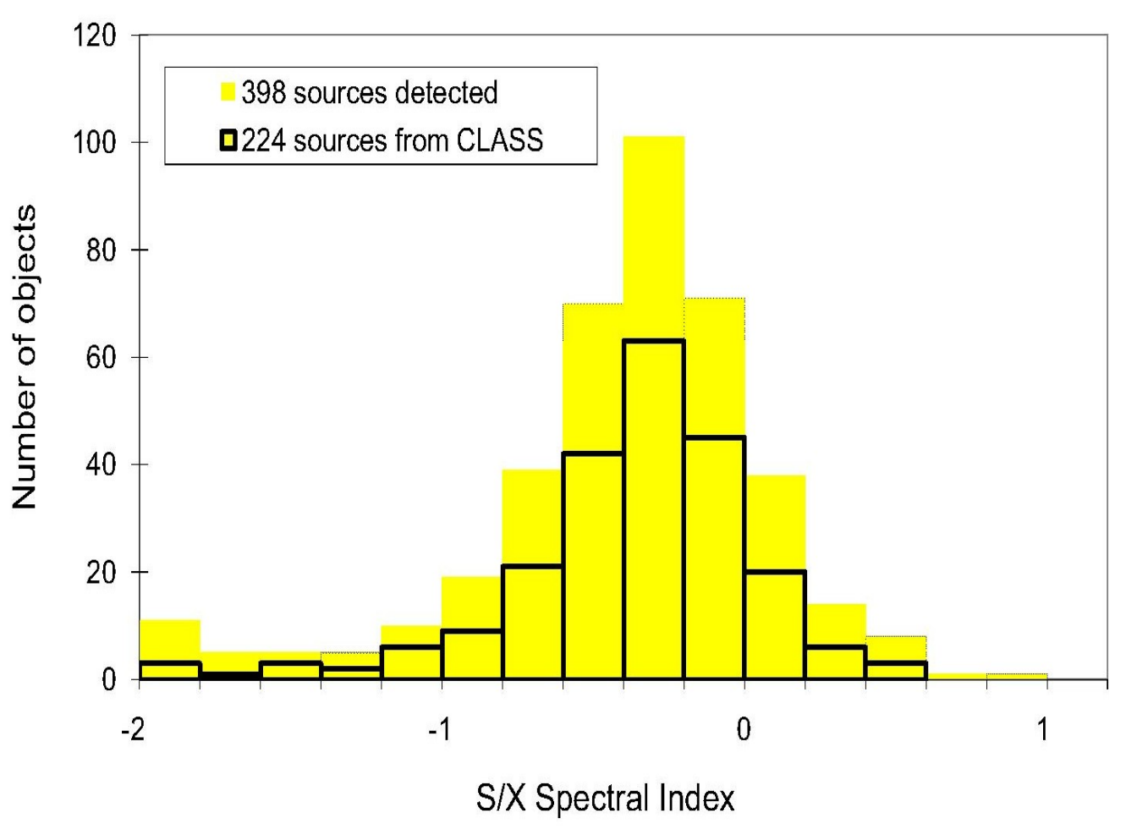


Figure 7: S/X spectral index distribution for the 398 weak extragalactic radio sources detected at both S and X bands, during EC025A and EC025B. The spectral index α is defined by: $S \propto \nu^{\alpha}$ (where S is the flux density and ν is the frequency). The corresponding distribution for the sources which also belong to the CLASS catalogue [14], well known to be composed of compact sources, is also plotted for comparison and no major differences are noticed.

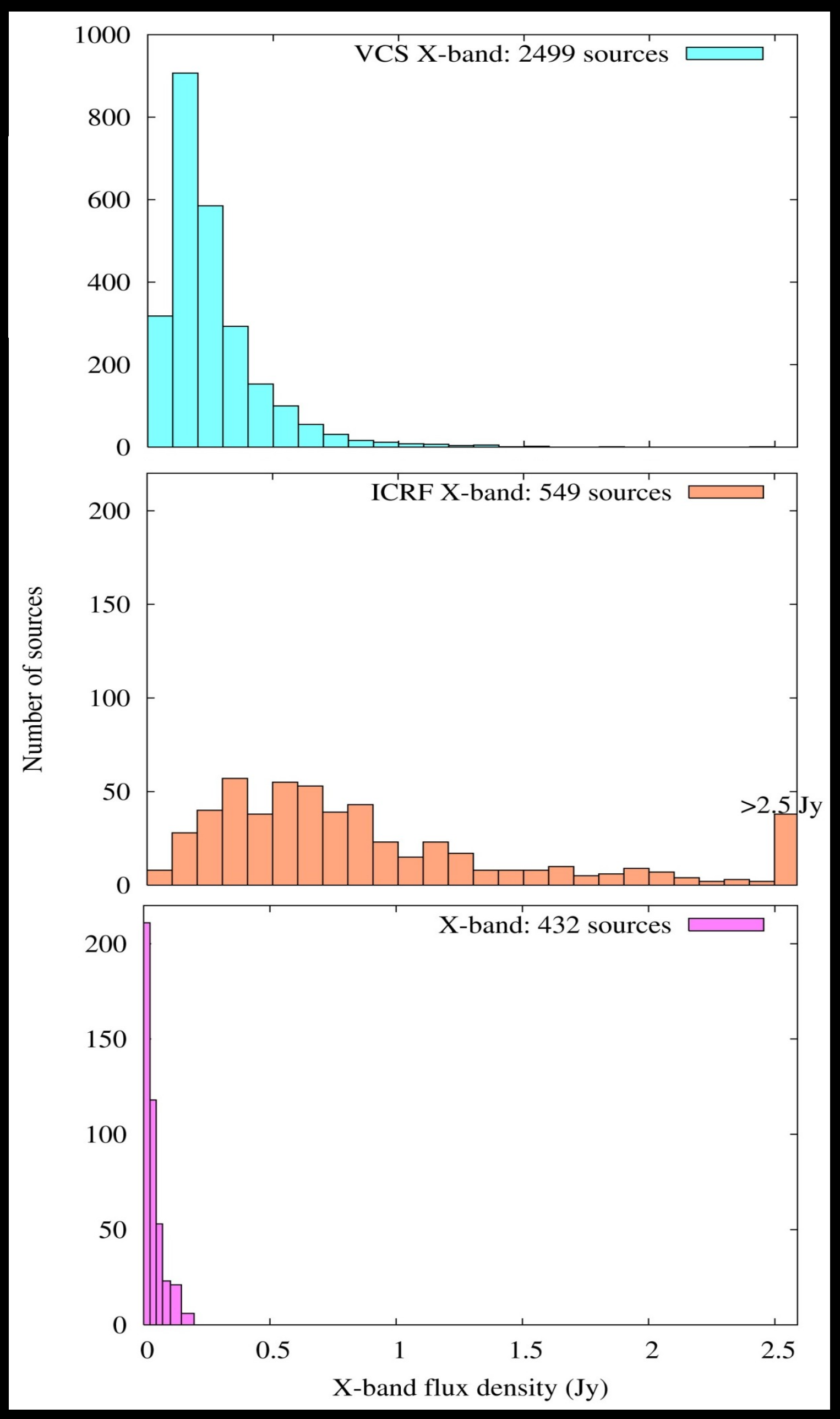


Figure 6: X-band flux density distribution (units in Jy) for the sources in VCS, ICRF and those detected in EC025A and EC025B.

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