EXTENDING AND IMPROVING THE INTERNATIONAL CELESTIAL REFERENCE FRAME

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ABSTRACT. The International Celestial Reference Frame (ICRF) currently includes a total of 667 extragalactic radio sources distributed over the entire sky, whose positions were measured based on data acquired with the Very Long Baseline Interferometry (VLBI) technique during the past two decades. This paper reviews the ongoing VLBI observational efforts to densify the frame with new sources and to extend the ICRF to higher radio frequencies. Analysis and modeling refinement to further improve the quality of the ICRF are also discussed with particular emphasis on astrophysical modeling of the emission structure of the sources.

1. THE INTERNATIONAL CELESTIAL REFERENCE FRAME (ICRF)

The International Celestial Reference Frame (ICRF) (Ma *et al.* 1998) became effective as the fundamental celestial reference frame on 1 January 1998, following a resolution adopted by the XXIIIrd General Assembly of the International Astronomical Union (IAU) on 1997 August 20 in Kyoto, Japan. The ICRF differs from the previous realization of the celestial frame, the FK5 stellar catalog, in two important ways: (i) it relies on extragalactic objects, and (ii) its axes are no longer related to the equator and ecliptic planes. Instead, the ICRF axes are specified through quasi-inertial coordinates of extragalactic objects, as measured with the Very Long Baseline Interferometry (VLBI) technique.

The VLBI data set used for the ICRF includes all applicable dual-frequency 2.3 GHz and 8.4 GHz Mark III VLBI measurements obtained from August 1979 to July 1995 (1.6 million pairs of group delay and phase delay rate observations). From a total of ∼600 extragalactic sources observed during this period, a subset of 212 sources distributed over the entire sky was selected to define the initial direction of the ICRF axes (Ma *et al.* 1998). These *defining* sources were chosen based on their observing histories with the VLBI networks and the stability and accuracy of their position estimates. The accuracy of the individual source positions is as small as 250 microarcseconds (μas) for the best objects while the orientation of the ICRF coordinate axes is good at the 20 μas level. Positions for 294 less-observed *candidate* sources and 102 *other* sources with less-stable coordinates were also reported, primarily to densify the frame (Ma *et al.* 1998). The first extension of the ICRF, ICRF–Ext.1, provides coordinates for an additional 59 *new* sources and refines the positions of candidate sources, based on further VLBI data acquired through April 1999 (IERS 1999).

Continued VLBI observation of the ICRF sources is essential to maintain the viability and integrity of the frame on the long term because extragalactic objects evolve in impredictable ways. Both their strength (total flux density) and radio structure (as imaged with high resolution VLBI) may change on time scales of a few months to a few years. The bulk of the observations for the ICRF maintenance is acquired through the so-called “RDV” (Research and Development with the VLBA) experiments. These are carried out every two months with a network comprising the 10 stations of the Very Long Baseline Array (VLBA)[1] plus other stations in North America, Europe, Asia and the Pacific. A total of ∼70 sources is observed in every RDV experiment and both the astrometric positions of these sources and images of their emission structures are derived from the data. Additionally, a small portion of certain geodetic VLBI sessions is used to observe ICRF sources so that each ICRF source, except in the far south, is observed recurrently.

Identification of new sources and modeling refinement are equally important to further improve the quality of the ICRF. Section 2 reviews the current VLBI observing programs for extending the ICRF. These include programs aimed at increasing the number of sources and programs to extend the frame to higher radio frequencies. The actual limitations to the VLBI astrometric accuracy are discussed in Sect. 3 with particular emphasis on the astrophysical modeling of the emission structure of the sources.

2. DENSIFICATION AND EXTENSION OF THE ICRF

The current observational efforts for extending the ICRF are directed towards either the densification of the frame at the standard geodetic observing frequencies (2.3 GHz and 8.4 GHz) or its extension to higher radio frequencies (24 GHz and 43 GHz). ICRF densification programs include single-epoch VLBI surveys to identify new candidate sources plus subsequent VLBI experiments dedicated to improve their astrometric positions, whereas ICRF extension experiments focus on observation of current ICRF sources. Each of these VLBI observing programs is discussed in turn below.

2.1 The VLBA Calibrator Survey

The VLBA Calibrator Survey (VCS1) (Beasley *et al.* 2002) consists of ten VLBA survey sessions conducted between August 1994 and August 1997, each of which observed a particular declination belt of 10–20° between −30° and +90° declination. The goals of this survey were: (*a*) to increase the surface density of known geodetic-grade calibrators with milliarcsecond-accurate positions, providing candidate sources for future extensions of the ICRF; (*b*) to facilitate routine VLBI phase-referencing to most regions of the northern and equatorial sky, allowing high-resolution radio imaging of weak scientific targets (Beasley & Conway 1995); and (*c*) to provide a uniform VLBI image data-base at 2.3 GHz and 8.4 GHz for use in scientific research, including active galactic nuclei and gravitational lensing studies, and cosmology.

Overall, a total of 1811 candidate calibrators were observed, most of which selected from the Jodrell Bank–VLA astrometric survey (Patnaik *et al.* 1992, Browne *et al.* 1998, Wilkinson *et al.* 1998). The analysis of this massive data set, recently published as the VCS1 catalog, reports unpreviously-measured VLBI astrometric positions for 1332 sources along with survey VLBI images[2] at 2.3 GHz and 8.4 GHz for most of these sources (Beasley *et al.* 2002). Two additional survey sessions have been carried out in January 2002 and May 2002 to fill existing holes in the VCS1 sky coverage of calibrators: in the declination range −20° to −45°; near the galactic plane; and for ICRF sources with somewhat limited structural information. These observed a further 500 potential calibrators which will form the basis for the VCS2 extension (Fomalont *et al.* 2002).

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[1] The VLBA is a facility of the National Radio Astronomy Observatory (NRAO) which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

[2] Available through the NRAO www site at http://magnolia.nrao.edu/vlba_calib/index.html.

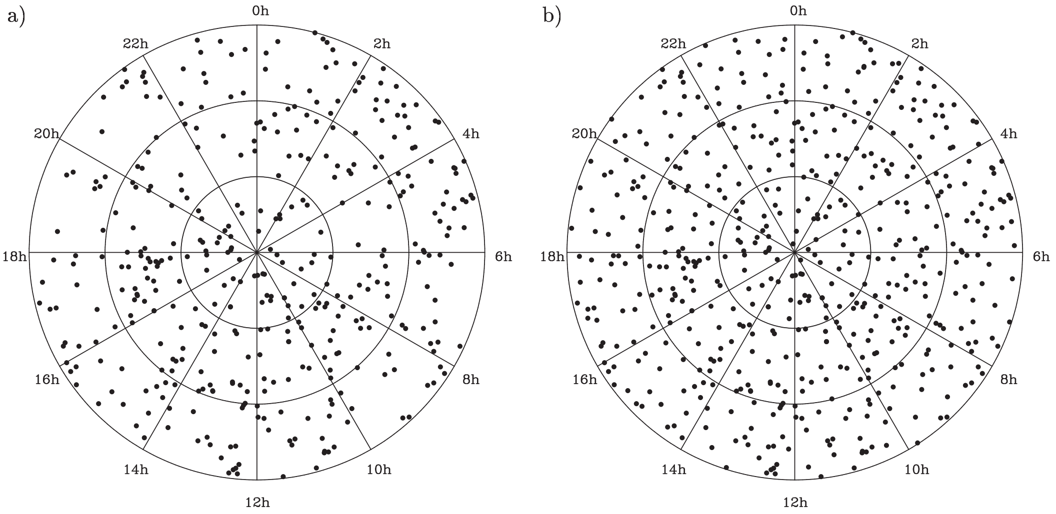

Figure 1: Northern-sky source distribution in polar coordinates: *a*) for the ICRF–Ext.1 frame; *b*) after completing the densification proposed by Charlot *et al.* (2000). The successive circles correspond to declinations of 0° (outer circle), 30°, 60°, and 90° (inner central point).

While the magnitude of the position errors is comparable for the ICRF–Ext.1 and VCS1 catalogs, it should be emphasized that the observing geometry of the VLBA Calibrator Survey was quite different from that of usual geodetic or astrometric sessions. Geodetic sessions attempt to observe uniformly the entire mutually visible sky as well as the local sky at each station to limit geometric and tropospheric systematic errors. As explained above, these conditions were not met in the VLBA Calibrator Survey, and it is possible that the VCS1 systematic errors are rather different. Additional observations of a large-enough sample of VCS1 sources in standard astrometric mode would thus be desirable to further assess the accuracy of this frame.

2.2 Densifying the northern sky

One of the deficiencies of the ICRF is the inhomogeneous sky distribution of the sources. While the frame contains an average of one source per 8° × 8° on the sky, the angular separation to the nearest ICRF source for any randomly-selected sky location is up to 13° in the northern sky and 15° in the southern sky (Charlot *et al.* 2000). This non-uniform coverage makes it difficult to assess and control any local deformations of the frame which for example might be caused by tropospheric propagation effects or the apparent motions of the sources due to their variable emission structures. It also precludes the use of the ICRF as a catalog of calibrators for phase-referencing observations because the angular separation between the calibrator and target source should be a few degrees at most in such observations (Beasley & Conway 1995).

As shown by Charlot *et al.* (2000), this deficiency could be largely reduced if adding a limited number of sources at specific sky locations. For example, an additional 150 sources in the northern sky would reduce the angular separation to the nearest ICRF source from a maximum of 13° to a maximum of 6°. This improvement is illustrated in Fig. 1 where the current northern-sky coverage in ICRF–Ext.1 is compared to that which would be obtained with such a densification. Based on the VLBA Calibrator Survey, Charlot *et al.* (2000) have further identified 150 such sources to fill the appropriate empty holes in the frame. Their source selection strategy was also designed to select only sources with no or limited extended structure, so that these constitute a priori high-quality candidates for the densifying the ICRF.

Observation of these sources was initiated in May 2000 with a large VLBI network of 12 telescopes comprising the European VLBI Network (EVN)[3] plus additional geodetic stations in USA and Canada. During this experiment, an initial 50 sources was observed, 49 of which were successfully detected, thus confirming that the source selection scheme was adequate. Preliminary astrometric analysis of these data indicates agreement at the milliarcsecond level with the VCS1 results for the majority of the sources. A further 50 sources have been observed in June 2002 with a similar VLBI network, the data of which should be correlated soon, while the rest of the sources is scheduled for observation in 2003.

2.3 Strengthening the southern sky

Another deficiency of the ICRF is the limited number of defining sources in the south (see the distribution of defining sources in Ma *et al.* 1998) and their somewhat less-accurate astrometric positions, as a result of the lack of well-established VLBI networks in the southern hemisphere. It is therefore of primary importance to devote special observational efforts to the southern sky to attempt to improve this situation in future ICRF realizations.

Along this line, a dedicated five-year observing program, including both astrometric and imaging experiments, has recently been initiated as a collaborative project between the US Naval Observatory (USNO) and the Australia Telescope National Facility (ATNF) (Fey *et al.* 2000). The objectives of this project are twofold: (*a*) improve the position accuracy of the existing southern ICRF sources and increase the density of candidate sources in the south; and (*b*) image at 8.4 GHz a complete sample of compact flat-spectrum sources south of -20° declination.

As reported by Ojha (2002), four full 24-hour astrometric sessions on existing ICRF sources along with short observations of 81 candidate sources have already been carried out. These used ATNF-accessible telescopes plus other geodetic stations in the southern hemisphere. Additionally, first-epoch VLBI imaging observations of 184 southern ICRF sources have been completed. Ultimately, the astrometric sessions should provide a strong tie between the northern and southern sky through the overlapping common sources at moderate southern declinations whose positions have already been measured with the northern VLBI networks.

2.4 Extension to higher radio frequencies

As mentioned above, the foundational work of the ICRF was done based on observations acquired at the standard geodetic frequencies of 2.3 GHz and 8.4 GHz. A number of developments have now converged to make future years an opportune time to pursue the extension of the ICRF to radio frequencies in the 24–43 GHz range. First, the 2.3 GHz environment is becoming increasingly cluttered by radio frequency interference making continued dual-frequency observations at 2.3 GHz and 8.4 GHz ever more difficult. Second, high-frequency amplifiers are now (24 GHz and 43 GHz) or will shortly be (32 GHz) available for use by the VLBI technique. Third, radio tracking systems for planetary probes are moving to the 32 GHz band and will soon require a sub-milliarcsecond-accurate high-frequency reference frame for deep space navigation. Additionally, extension to higher frequencies should enable improved VLBI astrometry, because the extragalactic sources are expected to be more compact at higher frequencies.

Based on this appreciation, a team of collaborators from several institutions (NASA, NRAO, USNO and Bordeaux Observatory) has been assembled in the fall of 2001 to initiate the extension of the ICRF in the 24–43 GHz range. As described by Jacobs *et al.* (2002), the major motivations for undertaking this large observational effort are: (*a*) to improve state-of-the-art VLBI astrometry; (*b*) to extend the list of VLBI calibrators in the 24–43 GHz range to enhance phase-referencing at high frequencies; (*c*) to study the high-frequency VLBI source morphology and its temporal evolution; and (*d*) to prepare for future deep space navigation. Along these lines, an initial proposal requesting VLBA observing time for three test experiments at 24 GHz and 43 GHz, with both astrometric and imaging goals, was approved in January 2002.

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[3] See http://www.evlbi.org/ for an overview of the European VLBI Network.

Table 1: VLBI systematic error budget (adapted from Jacobs *et al.* [1998])

Component of error	Error (μas)
Troposphere†	150–250
Instrumentation	50–100
Source structure	0–1000
A priori nutation model	20
Tides	20
Plasma effects	15
Relativity	10–40
Numerical stability	2

†Assuming that azimuthal asymmetries (tropospheric gradients) are modeled.

The first experiment, carried out in May 2002, observed 65 sources at 24 GHz and 43 GHz, all of which have been successfully detected and imaged at both frequencies. A comparison of these images with existing maps at lower frequencies (8.4 GHz and 2.3 GHz) confirms that the emission structures are generally more compact at high frequency. On the astrometric side, a preliminary analysis indicates consistency at the milliarcsecond level with the current ICRF source positions. The second experiment, carried out in August 2002, has just been correlated and is about to be analyzed, while the third experiment is planned for the end of year. Not awaiting the results of these, a new proposal has been submitted to the VLBA for further observing in 2003 based on this initial success.

3. IMPROVING THE ACCURACY OF THE ICRF

3.1 Limits on astrometric accuracy

Increasing the accuracy of VLBI astrometry requires improving the overall VLBI observing, calibration, and analysis system. This includes instrumentation as well as physical modeling of the observed VLBI quantities. Current estimates of the systematic "error budget" for VLBI astrometry, as that from Jacobs *et al.* (1998) in Table 1, provide directions for such improvements.

The troposphere causes the largest errors, at the level of 150–250 μas, mostly because of water vapor turbulence, temperature profile mismodeling, and mapping function approximations. The next largest errors are due to the instrumentation (atomic clock instabilities, receiver sensitivity, instrumental phase calibration errors) which may contribute a total of 50–100 μas. Source structure errors vary widely; for most of the sources, it is not the dominant error, but for a small fraction of them – perhaps 10% – it is the dominant error (see below for further details). Smaller errors are caused by nutation and tidal mismodeling, plasma effects (miscalibration due to the Earth's magnetic field, scintillation at low Sun angle), and relativistic mismodeling (both General Relativity and Special Relativity), which may each contribute from 10 to 40 μas, while numerical errors are thought to be negligible.

In the future, specific efforts should be directed at improving the troposphere calibration and modeling if significant reduction of the 250 μas systematic errors of the ICRF is to be sought. When this error is routinely reduced, e.g. by water-vapor-radiometer calibration (Naudet *et al.* 2002), the focus should be on instrumental calibration and source structure modeling. Recent progress for the latter is reviewed in the next section.

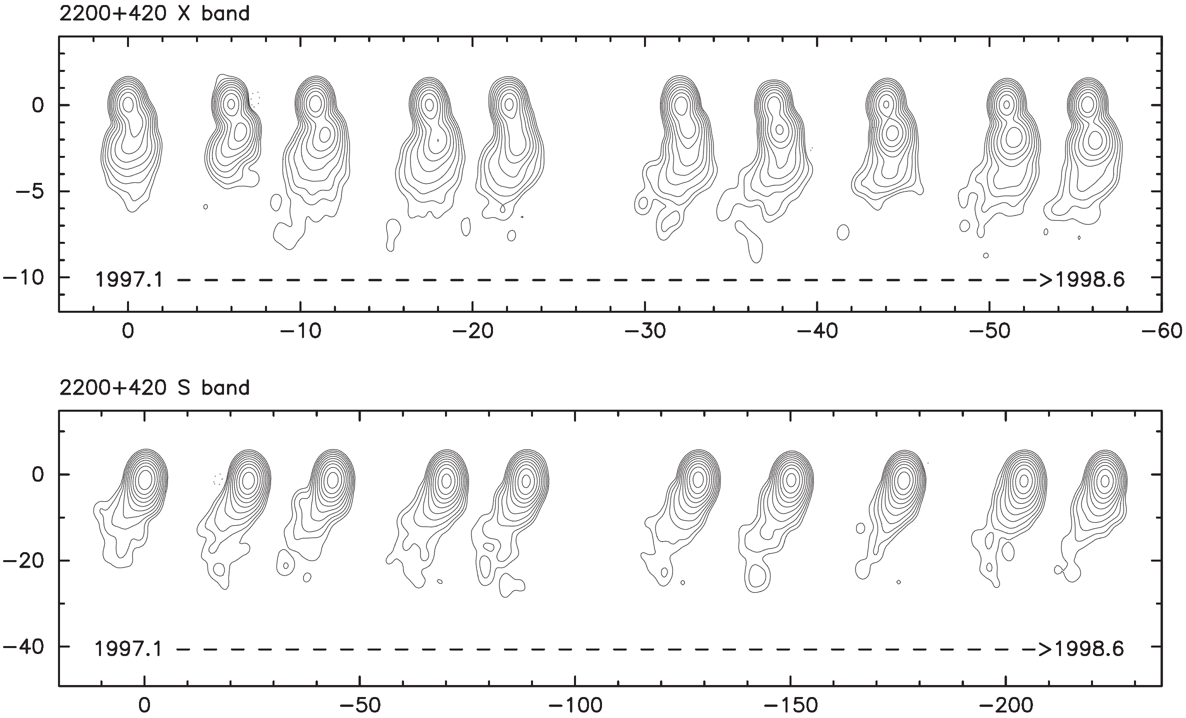

Figure 2: VLBI images of 2200+420 at 8.4 GHz (top panel) and 2.3 GHz (bottom panel) for 10 successive epochs spanning the period 1997.1–1998.6 (available from the USNO Radio Reference Frame Image Data Base). The maps are aligned horizontally according to the northern structural component (scale in milliarcseconds) and are spaced linearly according to their observing epochs. See Charlot (2002) for a discussion of source structure.

3.2 Astrophysical modeling of source structure

At the milliarcsecond scale, most of the extragalactic radio sources exhibit spatially-extended and variable emission structures which limit the VLBI astrometric accuracy if not modeled (Fey & Charlot 1997, 2000). The algorithm to model source structure (Charlot 1990) requires identification of a truly kinematically-stable morphological feature for each source and calculation of corrections derived from structure maps for the astrometric VLBI quantities. Exploratory work in this area showed that such modeling significantly improves the positional stability for the extended core-jet source 3C273 (1223+026) intensively observed during the 1980's, and reduces the rms delay residuals (Charlot 1994). A similar analysis based on VLBI data up to 1997 revealed that the long-term proper motion detected for the source 4C39.25 (0923+392) largely cancels out when incorporating source structure modeling, thus confirming that the peculiar systematic motion for this source is not real, but instead caused by its structural evolution (Charlot 2000).

Just recently, such exploratory studies have been extended to a much larger scale with a data set including 160 sources observed over up to 10 epochs and a total of 800 maps to correct for source structure (Sovers *et al.* 2002). Overall, the weighted rms delay residuals were found to decrease by 8 ps in quadrature upon introducing source maps to model the structure delays. The angular equivalent of this improvement is approximately 100 μas for typical VLBI baselines and amounts to a significant fraction of the 250 μas systematic error of the ICRF, thus confirming that source structure does affect VLBI analysis even though it is not currently the dominant error. For some sources with extended or fast-varying structures like the BL Lac object 2200+420 (see maps in Fig. 2), improvements were as large as 40 ps. In such cases, the scatter of the "arc" source positions over time was also found to decrease substantially (Fig. 3).

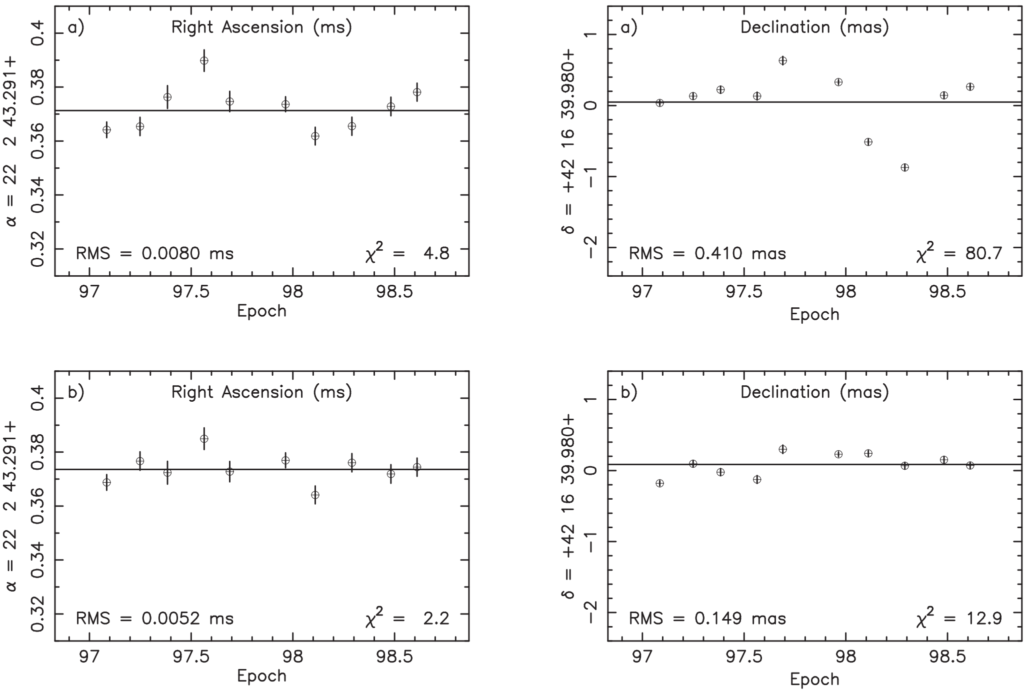

Figure 3: Estimated right ascension and declination coordinates of 2200+420 for 10 successive epochs spanning the period 1997.1–1998.6: *a*) no source structure modeling; *b*) with source structure modeled. Note the improved coordinate stability (reduced RMS scatter) for the latter. See Charlot (2002) for further details.

Future work in this area should be targeted at lengthening the time base, which was limited to 1.5 yr in the analysis of Sovers et al. (2002), in order to investigate source structure errors on longer time scales. Detailed studies of time sequence of maps are also necessary to permit identification of the invariant fiducial points within individual sources and further improve modeling (see Charlot [2002] for a discussion of this aspect).

4. CONCLUSION

The ICRF, as realized by VLBI astrometry, has been a great step forward. Compared with previous stellar realizations of the celestial frame, it is intrinsically simpler, much more accurate, more stable, and less susceptible to systematic errors, even though it requires continued VLBI observations to maintain these qualities on the long term. Further observations are underway to strengthen the southern sky, to densify the frame, and to extend it to other radio frequencies for wider applications of the ICRF. On the modeling side, the major areas to focus on for further improvements are the troposphere calibration and modeling, the instrumental calibration, and source structure modeling.

Immediate attention within the next year will be focused on the preparation of the 2003 IAU General Assembly. Current plans include: (*a*) assembling a second ICRF extension – with similar modeling as for ICRF and ICRF–Ext.1 and no revision of source categories – in order to publish the positions of the new sources observed since 1999; (*b*) detailed investigations of how a new ICRF realization could be improved upon ICRF (modeling refinement, revised analysis strategies, handling of source structure and source position variations); and – if time permits – (*c*) generation of a prototype ICRF–2 with revised *defining*, *candidate*, and *other* source categories.

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