OPTICAL SPECTRA OF CANDIDATE INTERNATIONAL CELESTIAL REFERENCE FRAME (ICRF) FLAT-SPECTRUM RADIO SOURCES

O. TITOV¹, LAURA M. STANFORD¹, HELEN M. JOHNSTON², T. PURSIMO³, RICHARD W. HUNSTEAD²,
DAVID L. JAUNCEY⁴, K. MASLENNIKOV⁵, AND A. BOLDYCHEVA⁶

¹ Geoscience Australia, P.O. Box 378, Canberra, ACT 2601, Australia; oleg.titov@ga.gov.au

² Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia

³ Nordic Optical Telescope, Nordic Optical Telescope Apartado 474E-38700 Santa Cruz de La Palma, Santa Cruz de Tenerife, Spain

⁴ CSIRO Astronomy and Space Science, ATNF & Research School of Astronomy & Astrophysics, Australian National University, Canberra, ACT 2611, Australia

⁵ The Central Astronomical Observatory at Pulkovo, Pulkovskoye Shosse, 65/1, 196140, St. Petersburg, Russia

⁶ Ioffe Physical Technical Institute, 26 Polytekhnicheskaya, St. Petersburg, 194021, Russia

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ABSTRACT

Continuing our program of spectroscopic observations of International Celestial Reference Frame (ICRF) sources, we present redshifts for 120 quasars and radio galaxies. Data were obtained with five telescopes: the 3.58 m European Southern Observatory New Technology Telescope, the two 8.2 m Gemini telescopes, the 2.5 m Nordic Optical Telescope (NOT), and the 6.0 m Big Azimuthal Telescope of the Special Astrophysical Observatory in Russia. The targets were selected from the International VLBI Service for Geodesy & Astrometry candidate International Celestial Reference Catalog which forms part of an observational very long baseline interferometry (VLBI) program to strengthen the celestial reference frame. We obtained spectra of the potential optical counterparts of more than 150 compact flat-spectrum radio sources, and measured redshifts of 120 emission-line objects, together with 19 BL Lac objects. These identifications add significantly to the precise radio–optical frame tie to be undertaken by *Gaia*, due to be launched in 2013, and to the existing data available for analyzing source proper motions over the celestial sphere. We show that the distribution of redshifts for ICRF sources is consistent with the much larger sample drawn from Faint Images of the Radio Sky at Twenty cm (FIRST) and Sloan Digital Sky Survey, implying that the ultra-compact VLBI sources are not distinguished from the overall radio-loud quasar population. In addition, we obtained NOT spectra for five radio sources from the FIRST and NRAO VLA Sky Survey catalogs, selected on the basis of their red colors, which yielded three quasars with $z > 4$.

Key words: BL Lacertae objects: general – galaxies: active – quasars: emission lines – radio continuum: general – reference systems

Online-only material: color figures, extended figure, machine-readable and VO tables

1. INTRODUCTION

The coming astrometric space mission, *Gaia* (Perryman et al. 2001; Mignard & Klioner 2012), to be launched in 2013 by the European Space Agency, will measure high precision positions ($\sim 26 \mu\text{as}$ for $V = 15$ mag, $\sim 300 \mu\text{as}$ for $V = 20$ mag; de Bruijne 2012) and proper motions of $\sim 500,000$ quasars brighter than $m_v = 20$. This new optical astrometric catalog will be linked with the current radio astrometric catalog, ICRF2, the second realization of the International Celestial Reference Frame (Fey et al. 2009). Optical counterparts of the extragalactic sources are being sought to confirm their identification as quasars.

This paper is the second in our series aimed at investigating the optical spectra of radio sources in the International VLBI Service for Geodesy & Astrometry (IVS) Reference Catalog; see Schlüter & Behrend (2007) for a description of the IVS history. Astrometric very long baseline interferometry (VLBI) measures the differences in arrival times of radio waves from ultra-compact, flat-spectrum radio sources at telescopes positioned large distances apart. This procedure determines the positions of such sources to milliarcsecond precision.

The International Celestial Reference System (ICRS; Arias et al. 1995) was adopted by the International Astronomical Union as a reference system with its origin at the barycentre of the solar system (MacCarthy & Petit 2004), and axes fixed

by the positions of selected extragalactic radio sources. The first realization of the International Celestial Reference Frame (ICRF1) was used to establish the orientation of the ICRS axes (Ma et al. 1998). The current International Celestial Reference Frame, known as ICRF2, is based on a catalog of 295 “defining” sources. The formal weighted errors in the radio positions are reported by Fey et al. (2009) to have an upper limit to the noise floor of $41 \mu\text{as}$.

The IVS astrometric program has a total catalog of >6000 radio sources, where ~ 1200 are observed on a regular basis. In the Southern Hemisphere, there is a significant deficit in candidate sources as well as a lack of optical identifications. By 2012 February, of the 3257 objects with measured redshifts, only 1213 are in the southern hemisphere and only 287 have declinations south of -40° . This paucity of redshifts in the south leads to problems in the analysis of apparent proper motions of the reference radio sources (Titov & Malkin 2009). To address this issue, an extensive program was started in 2010 to find optical counterparts and determine redshifts for southern IVS sources (Titov et al. 2011).

The quasars at high redshift ($z \geq 2$) will be used for more intensive observations at the VLBI facilities in the southern hemisphere. VLBI observations of weak sources will be undertaken with the 64 m telescope in Parkes, Australia, and two 26 m telescopes in Hobart (Australia) and HartRAO (South Africa). Stronger radio sources (flux density ≥ 400 mJy) will

be monitored with four 12 m telescopes recently installed in Australia: the AuScope network comprising Hobart, Yarragadee, and Katherine in Australia (Titov et al. 2013), and Warkworth in New Zealand. Several quasars found during the first observing run with the New Technology Telescope (NTT) in 2010 August (Titov et al. 2011) have now been tracked with the AuScope radio telescopes in 2011–2012.

In this paper, we continue our spectroscopic observations of the optical counterparts of southern IVS sources, in particular those with a long VLBI observational history. Some strong radio sources from the northern hemisphere have also been observed. Optical identifications were sought initially from the image and catalog data from the SuperCOSMOS Sky Surveys on the grounds of their small digitization pixel scale and excellent astrometric accuracy (Hambly et al. 2001). We also took advantage of the Sloan Digital Sky Survey (SDSS; York et al. 2000) DR8 in the regions where it was available. This improved the identification process, especially in regions of high stellar density.

In addition, we observed five weaker radio sources from the NVSS (NRAO VLA Sky Survey; Condon et al. 1998) and FIRST catalogs (Faint Images of the Radio Sky at Twenty cm; Becker et al. 1995) that we identified with objects from the SDSS whose colors were typical of high redshift quasars. Such high redshift quasars provide unique information about the early stages of the universe. The number of known radio sources with $z \geq 4$ is small, and we are exploiting this technique in an attempt to increase their number.

The observations and data reduction procedures are described in Section 2 and we report our results, along with detailed comments on individual objects, in Section 3.

2. OBSERVATIONS

Spectroscopic observations were carried out at five optical facilities.

ESO NTT. We had a five-night observing run in Visitor Mode at the European Southern Observatory (ESO) 3.58 m NTT at La Silla in 2011 December (088.A-0021 (A)) using the ESO Faint Object Spectrograph and Camera system with grism 13 covering the wavelength range 3685–9315 Å. The seeing during observations was typically 0".5–1".5, with a wavelength resolution 21.2 Å. Exposure times varied from 10 minutes to 1 hr depending on the magnitude of each target and current sky conditions. Wavelength calibration was performed using the spectra of an HeNeAr comparison lamp, resulting in an rms accuracy of 0.5 Å.

Gemini. A large number of targets were observed in Service Mode at the Gemini North and Gemini South 8.2 m telescopes through the Poor Weather Program (GS-2011A-Q-89, GN-2011B-Q-109, GS-2011A-Q-94) using the Gemini Multi-Object Spectrograph system with grating R400. This grating covers 4500 Å centered either at 5200 Å or 6500 Å. As expected, the seeing and weather conditions were variable but the program overall was very successful. The wavelength resolution was ~ 15 Å, and an exposure time of 20 minutes was used for all targets. Wavelength calibration was performed using the spectra of a CuAr lamp, resulting in an rms accuracy of ~ 0.3 Å.

NOT. Observations with the 2.5 m Nordic Optical Telescope (NOT) on La Palma were carried out using the Andalucia Faint Object Spectrograph and Camera spectrograph, either with grism 5 or grism 4 with the WG345 blocking filter. The nominal wavelength range for grism 4 is 3200–9100 Å, with the second-order blocking filter cutting below 3560 Å. The

red end of the detector suffers fringing, so the effective long-wavelength limit is about 8000 Å. For grism 5 the nominal range is 5000–10250 Å. The slit width was 1"0 or 1"3 depending on the seeing. The typical integration time was between 20 and 40 minutes. The longer integrations were divided into two and the target was offset along the slit in order to improve the fringe correction. For the single integrations, internal halogen lamp images were taken before and after the science frame. Wavelength calibration was based on an HeNe lamp exposure taken before the science frame(s), resulting in an rms accuracy of ~ 0.5 Å.

BTA. Two objects were observed in Visitor Mode at the 6 m Big Azimuthal Telescope (BTA) telescope of the Special Astrophysical Observatory in Russia in 2011 August, using the SCORPIO multi-mode focal reducer with GR300 grism covering the wavelength range 3500–9500 Å. The seeing during observations was about 2". Spectral resolution was typically 20 Å.

Data reduction was performed with the IRAF software suite⁷ using standard procedures for spectral analysis. We removed the bias and pixel-to-pixel gain variations from each frame and then removed cosmic rays using the IRAF task SZAP. Where more than one exposure was obtained, the separate exposures were combined. Spectrum extraction, sky subtraction, and wavelength calibration were then carried out and the final one-dimensional spectra were flux-calibrated with a spectrophotometric standard observed with the same instrumental setup. Because the conditions were often non-photometric, especially for observations made through the Gemini Poor Weather Program, the flux calibration should be taken as approximate.

3. RESULTS

Spectra of 120 IVS objects are shown in Figure 1, along with the line identifications. A blue, dashed line indicates lines that were used for redshift calculation, while a red, dot-dashed line indicates lines that were detected, generally at a low signal-to-noise ratio (S/N), but not used in determining the mean redshift.

Table 1 lists the IVS sources with their ICRF2 coordinates (which refer to the epoch J2000.0), the telescope used for each spectrum, the identified emission lines with their rest and observed wavelengths, the mean redshift and error, and brief notes on individual sources. More detailed notes on individual sources (indicated by an asterisk in the final column) are given in Section 3.2.

The quoted errors Δz in the mean redshift $\bar{z}$ are given by

$$\Delta z = \{[(\sigma_z)^2 + (\Delta\lambda/\bar{\lambda}_0)^2]/N\}^{1/2},$$

where σ_z is the measured standard deviation among the independent estimates of z , $\Delta\lambda$ is the rms error in the wavelength calibration (typically 0.5 Å), and $\bar{\lambda}_0$ is the mean rest wavelength of the N lines used to measure $\bar{z}$. Single-line redshifts (mostly Mg II) are assigned a conservative error of 0.001 if the S/N is high and the line is symmetric. If the S/N is low or the line is broad or asymmetric, then an (arbitrary) error of 0.002 is assigned; in two extreme cases where the S/N is low and the line is broad or asymmetric (IVS B0633–26B and B1129–161), the redshift is given with a colon(:) appended and no error.

⁷ IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

Figure 1. Optical spectra for 120 emission-line IVS targets. Dashed lines (blue) indicate emission lines used for redshift determination; dot-dashed lines (red) indicate lines detected at a lower signal-to-noise ratio or blended.

(An extended, color version of this figure is available in the online journal.)

Table 1
Observed Emission Lines

Source	R.A. (J2000) ^a	Decl. (J2000) ^a	Telescope ^b	Line	Rest λ	Obs λ ^c	$\bar{z}$	Note ^d
IVS B0022–227	00 25 24.2474	–22 27 47.596	GS	Mg II	2799.9	5136.3	0.834 ± 0.001	S
IVS B0032+276	00 34 43.4861	+27 54 25.721	BTA	Ly α	1215.7	4820.4		
				N V	1240.1	[4921.7]		
				Si IV	1398.3	[5545.9]		
				C IV	1549.5	6141.2	2.9642 ± 0.0009	
IVS B0044–846	00 44 26.6883	–84 22 39.988	GS	Mg II	2799.9	5697.2	1.035 ± 0.001	S $z = 1.032$ [S12]
IVS B0205–619	02 06 40.0029	–61 43 32.206	NTT	C III]	2326.9	[4032.5]		
				Mg II	2799.9	4855.9		
				[O II]	3726.8	6454.0		
				[Ne III]	3868.7	6694.0		
				[O III]	5006.8	8661.5	0.7316 ± 0.0010	
IVS B0206–625	02 08 01.1713	–62 16 35.533	GS/NTT	Ly α	1215.7	4114.9		
				N V	1240.1	[4198.6]		
				Si IV	1398.3	[4733.6]		
				C IV	1549.5	5237.6		
				C III]	1908.7	6451.8	2.3817 ± 0.0016	
IVS B0213–015	02 16 05.6638	–01 18 03.397	GS	Ly α	1215.7	4624.9		
				N V	1240.1	[4720.2]		
				Si IV	1398.3	[5326.7]		
				C IV	1549.5	5887.3		
				C III]	1908.7	7261.7	2.8028 ± 0.0017	
IVS B0219–637	02 20 54.1727	–63 30 19.387	GS	C III]	1908.7	4730.2		
				Mg II	2799.9	6937.4	1.4780 ± 0.0003	
IVS B0226–375	02 28 33.7343	–37 19 56.338	NTT	Ly α	1215.7	3842.4		
				Si IV	1398.3	[4408.5]		
				C IV	1549.5	4881.0		
				C III]	1908.7	6014.0	2.1538 ± 0.0034	
IVS B0233–478	02 35 06.4235	–47 37 10.574	GS	Al III	1858.8	[4692.1]		
				C III]	1908.7	[4784.9]		
				Mg II	2799.9	7011.2	1.504 ± 0.001	S *
IVS B0301–721	03 01 38.4456	–71 56 34.399	GS	Mg II	2799.9	5105.8		
				[O II]	3726.8	6795.7		
				[Ne III]	3868.7	7051.2	0.8232 ± 0.0003	
IVS B0318–388	03 20 46.4048	–38 37 28.503	NTT	C III]	1908.7	4191.0		
				Mg II	2799.9	6151.3	1.1964 ± 0.0006	

Notes.

^a ICRF2 radio position.

^b Telescope abbreviations: BTA = Big Azimuthal Telescope, GS = Gemini North, NOT = Nordic Optical Telescope, NTT = ESO New Technology Telescope.

^c Square brackets indicate the line was not used for redshift determination.

^d “S” denotes a single-line redshift; * indicates a note in Section 3.2. Previously determined redshifts are from: [A09] Afanas’ev et al. (2009); [S12] Shaw et al. (2012); [S] Simbad database; [6dF] 6dF survey, Jones et al. (2009).

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Nineteen objects, listed in Table 2 with their ICRF2 positions (Fey et al. 2009), were found to have a good S/N (typically ~ 60 –110) but featureless spectra, and hence are identified as probable BL Lac objects. Their spectra are shown in Figure 2.

A further 18 targets had spectra with an S/N that was too low for confident spectral classification; these are listed in Table 3 with their ICRF2 positions.

There were five IVS targets that returned stellar spectra. This was assumed to be the result of foreground obscuration and, in most cases, small but significant offsets between SuperCOSMOS optical and ICRF2 radio positions. In two cases, the correct identification was found when the fields were reobserved in excellent seeing. Further discussion of these five objects is given in Section 3.1.

3.1. Separation of Close Objects

Occasionally, Galactic stars are found close on the sky to the radio position, leading to possible misidentification. Here we

note several cases that were encountered during the observing runs.

1. IVS B0900–664—the spectrum obtained was that of a red M star, which is offset by $0''.52$ from the ICRF position. A faint counterpart was seen in the NTT *B*-band acquisition image, but a much longer integration in good seeing will be needed to secure a redshift.
2. IVS B0905–202—the nearest object, as seen by SuperCOSMOS, was an $R = 14^m.6$ stellar object located $1''.55$ from the radio position. Our NTT acquisition image, taken in $0''.6$ seeing, showed a faint object at the radio position, but on the limb of the stellar disk. Spectroscopy of this faint $R \sim 22$ object did not reveal any clear emission lines.
3. IVS B1657–261—located in a very crowded star field in the Galactic bulge at a latitude of $b = 9^\circ.7$. Identification of the optical counterpart may not be feasible.
4. IVS B1946–582—based on the SuperCOSMOS optical position, the radio minus optical position difference is only

Figure 2. Spectra of 19 probable BL Lac objects from our observations, classified on the basis of their featureless spectra; see Table 2 for ICRF2 positions.

Figure 2. (Continued)

$0^{\circ}06$ in right ascension and $-0^{\circ}04$ in declination, but the Gemini South observation of this $R \sim 19$ object showed a typical stellar spectrum. The radio source has a flat spectrum with flux density 200–300 mJy at cm wavelengths.

5. IVS B2300–307—the obscuration of the optical field of this source by a foreground star was discussed previously (Titov et al. 2011). However, a later 80 s image in $0^{\circ}6$ seeing (Figure 3) revealed a faint $R \sim 22$ object coincident with the radio position. Our spectroscopy yielded a redshift of 1.039 ± 0.002 based on weak C III] and Mg II emission.

3.2. Notes on Individual Targets

1. IVS B0233–478—the broad feature attributed to Al III and C III] may also include Si III $\lambda 1890$.
2. IVS B0417–302—prominent Fe II multiplet emission; intervening Mg II doublet absorption at $z_{\text{abs}} = 0.8395 \pm 0.0005$.
3. IVS B0447–507—possible double-peaked C III] line and prominent Fe II multiplet bands.

Figure 3. Two acquisition images of the sky field around the quasar IVS B2300–307 made at the NTT in 2010 August (left: seeing $2''$) and 2011 December (right: seeing $0^{\circ}6$). Each image is $50''$ on a side; north is up and east to the left. The foreground star in the center of the left image completely obscures the quasar due to its large seeing disk. In the right image, the much better seeing reveals the faint quasar ($R \sim 22$, marked between the bars), separated by $3^{\circ}7$ from the star. (The diagonal step in contrast in the right image is an artifact of fast readout using two amplifiers for the acquisition image.)

4. IVS B0448–482—poor redshift match to C III] may indicate the presence of Si III $\lambda 1890$; prominent Fe II multiplet bands.

Table 2
Probable BL Lac Objects

Source	R.A. (J2000) ^a	Decl. (J2000) ^a	Telescope
IVS B0026–710	00 28 41.5626	–70 45 15.926	GS
IVS B0313–171	03 15 27.6783	–16 56 29.711	NTT
IVS B0608–187	06 10 17.8861	–18 47 40.090	GS
IVS B0633–263	06 35 20.9090	–26 20 39.866	NTT
IVS B0700–661	07 00 31.2531	–66 10 45.232	NTT
IVS B0729–826	07 23 39.4063	–82 47 41.089	NTT
IVS B0744–158	07 46 18.2360	–15 55 34.745	NTT
IVS B0752–116	07 54 26.4564	–11 47 16.948	GS
IVS B0804–055	08 07 09.6175	–05 41 13.914	NTT
IVS B0815–094	08 17 49.7495	–09 33 30.528	GS
IVS B1123–356	11 25 31.4818	–35 57 03.352	NTT
IVS B1424–328	14 27 41.3610	–33 05 31.505	GS
IVS B1922–224	19 25 39.7901	–22 19 35.112	GS
IVS B1942–313	19 45 59.3693	–31 11 38.356	GS
IVS B1951–115	19 54 41.1557	–11 23 22.641	GS
IVS B2022–289	20 25 53.6128	–28 45 48.697	GS
IVS B2036–109	20 39 00.7104	–10 46 41.863	GS
IVS B2104–668	21 08 51.8207	–66 37 22.744	GS
IVS B2240–064	22 43 08.7606	–06 09 02.567	GN

Note. ^a ICRF2 radio position.**Table 3**
Objects with Low Signal-to-noise Spectra

Source	R.A. (J2000) ^a	Decl. (J2000) ^a	Telescope
IVS B0205–242	02 07 33.3992	–24 02 02.210	NTT
IVS B0227–542	02 29 12.7856	–54 03 24.036	NTT
IVS B0244–050	02 46 49.1315	–04 51 10.933	NTT
IVS B0253–754	02 53 10.8816	–75 13 16.686	GS
IVS B0334–546	03 35 53.9248	–54 30 25.114	NTT
IVS B0458+138	05 01 45.2708	+13 56 07.220	NTT
IVS B0516–621	05 16 44.9261	–62 07 05.389	NTT
IVS B0600+219	06 03 51.5570	+21 59 37.698	GN
IVS B0628–627	06 28 57.4877	–62 48 44.744	NTT
IVS B0705–649	07 05 26.0526	–65 00 43.484	NTT
IVS B0718–523	07 19 14.2919	–52 28 32.506	NTT
IVS B0821–094	08 23 52.0233	–09 39 25.907	NTT
IVS B0905–202	09 07 54.0404	–20 26 49.475	GS
IVS B0939–077	09 42 21.4614	–07 59 53.204	GS
IVS B1118+073	11 20 38.4438	+07 04 47.174	NTT
IVS B1134–739	11 36 09.6597	–74 15 45.274	NTT
IVS B1821–525	18 25 13.8097	–52 30 58.281	GS
IVS B2020–015	20 23 32.8163	–01 23 42.153	GS

Note. ^a ICRF2 radio position.

5. IVS B0521–262—strong associated absorption in the Ly α emission line and a clear detection of the Lyman limit at the emission redshift.
6. IVS B0529–031—faint optical counterpart with a very red spectrum, showing a single broad emission line identified as Mg II with associated Mg II absorption at $z_{\text{abs}} = 1.8744 \pm 0.0004$, corresponding to a relative blue-shift of $\sim 1500 \text{ km s}^{-1}$; a further absorption line at 8182.1 Å remains unidentified. Given the low signal blueward of 6000 Å, together with the faint SDSS blue magnitudes ($u = 24.41$, $g = 21.93$), it is not surprising that C III] and C IV are not detected.
7. IVS B0548–527—redshift in Table 1 is for the forbidden lines; the permitted lines of Mg II and H β show a redshift systematically higher by $830 \pm 80 \text{ km s}^{-1}$.
8. IVS B0554+242—narrow self-absorption in Ly α and C IV at $z_{\text{abs}} = 3.2319 \pm 0.0010$.
9. IVS B0608–230—wavelengths for C III] and C IV are not consistent, suggesting the presence of additional lines or asymmetric structure; in addition, the Ly α wavelength is likely to be affected by absorption in the blue wing.
10. IVS B0633–26B—a very faint galaxy; a low S/N spectrum, with a single broad emission line, assumed to be Mg II.
11. IVS B0810–180—very broad line wings in C IV and Ly α , extending $\sim 30,000 \text{ km s}^{-1}$ redward of the line peaks.
12. IVS B0828–064—poor consistency in redshift between C IV and C III], possibly due to associated absorption in the blue wing of C IV. Mg II is present with a low S/N just redward of the atmospheric A-band.
13. IVS B0844–557—redshift in Table 1 is for the forbidden lines; permitted lines Mg II and H β are displaced $\sim 1000 \text{ km s}^{-1}$ to higher redshift.
14. IVS B0948–860—single emission line, assumed to be Ly α ; the adopted redshift, $z = 3.696$, is consistent with the 40% continuum depression blueward of the emission line due to the Ly α forest, and the possible detection of C IV at the red edge of the spectrum.

15. IVS B0952–185—associated absorption at the emission redshift in both Ly α and C IV.
16. IVS B0956–409—Ly α is strongly self-absorbed.
17. IVS B1004–125—reported as having $z = 0.24$ in Simbad (no reference given), clearly inconsistent with our Gemini spectrum; strong intervening heavy-element system at $z_{\text{abs}} = 1.5786 \pm 0.0002$ based on Fe II $\lambda\lambda 2344, 2382, 2586, 2600$ and Mg II $\lambda\lambda 2796, 2803$ absorption.
18. IVS B1020+270—extended red wing in C IV; C III] is not detected due to strong CCD fringing.
19. IVS B1039–474—Si IV, C IV and C III] emission lines all show strongly extended blue wings; redshift is based on the peak positions of the lines.
20. IVS B1127–443—single-line redshift is supported by stellar absorption features (G-band, Mg IIb) noted in the plotted spectrum.
21. IVS B1143–696—spectrum is very similar to that of 3C 273, with strong Fe II multiplet emission in the region around H β (Wampler & Oke 1967).
22. IVS B1722+562—strong associated absorption system at $z_{\text{abs}} = 2.2463 \pm 0.0002$ seen in C IV, Si IV, N V and Ly α . This has led to a relatively large uncertainty in emission redshift.
23. IVS B2235–556—strong self-absorption in the red wing of C IV.
24. IVS B2334–525—broad Mg II, possibly double-peaked with an extended red wing.
25. IVS B2341+295—very blue object based on POSS II sky survey images; rise in the spectrum redward of 7000 Å may be due to the underlying galaxy or an unrelated object on the spectrograph slit. Intervening Mg II absorber at $z = 0.8644 \pm 0.0004$.

3.3. Spectra of Color-selected Quasars

In an attempt to find more high-redshift radio quasars for our VLBI proper motion studies as a function of redshift, we selected five weak radio sources from the FIRST and NVSS catalogs for which the SDSS colors suggested the likelihood of u - or g -band dropouts and the possibility of high redshifts.

Table 4
SDSS Magnitudes and Redshifts for Five Color-selected NVSS Radio Sources

Source	R.A. (J2000) ^a	Decl. (J2000) ^a	<i>g</i>	<i>r</i>	Telescope ^b	Line	Rest λ	Obs λ ^c	<i>z</i> ^d
NVSS J101335+281118	10 13 35.49	+28 11 18.3	25.76	22.03	NOT	Ly α	1215.7	6990	
						Ly β	1025.7	5897	4.75:
NVSS J125944+240707	12 59 44.59	+24 07 07.9	22.94	21.82	NOT	Mg II	2799.9	5895.5	1.138 $\pm$ 0.001
NVSS J145459+110928	14 54 59.36	+11 09 28.5	26.09	22.67	NOT	Ly α	1215.7	7208	4.93:
NVSS J162830+115403	16 28 30.55	+11 54 03.5	25.27	22.25	NOT	Ly α	1215.7	6650	4.47:
NVSS J163400+640821	16 34 00.47	+64 08 21.6	24.67 ^e	19.57 ^e	NOT	Ly α	1215.7	[5628.4]	
						O I/Si II	1303.3	[6039.0]	
						Si IV	1398.3	[6458.1]	
						C IV	1549.5	7157.7	3.619 $\pm$ 0.001

Notes.

^a NVSS radio position.

^b Nordic Optical Telescope.

^c Square brackets indicate the line was not used for redshift determination.

^d Colon indicates approximate redshift based on Ly α alone.

^e Magnitudes are *u* and *g*, respectively, for this object.

Spectra were obtained at the NOT on the nights of 2012 May 24–26. The SDSS colors, wavelengths, and redshifts for the five color-selected radio quasars are given in Table 4. The “bluest” of the five, NVSS J125944+240707, was a $z = 1.139$ radio galaxy, but the other four proved to be broad emission-line quasars with redshifts in excess of 3.5, including three with $z > 4$. This is an excellent return for our search and a striking result from the NOT, the smallest of the telescopes used in this program. The five spectra are shown in Figure 4 and further information is given in Table 4. Redshifts for the $z > 4$ quasars are based on estimated wavelengths for Ly α (and, in one case, Ly β) and are very uncertain because of strong absorption in the blue wing of the line.

A comparison between the FIRST and NVSS flux densities at 1.4 GHz for the five sources showed that one source, NVSS J145459+110928, appeared to show evidence of variability, with $S_{\text{NVSS}} = 9.8 \pm 0.5$ mJy and $S_{\text{FIRST}} = 15.07 \pm 0.14$ mJy. This is also the only source that is unresolved in FIRST. The other four sources all show minor extension at the 1'' level.

4. REDSHIFT DISTRIBUTIONS

Together with the 31 redshifts reported in Titov et al. (2011), we have now accumulated over 150 redshifts for IVS sources, mostly in the south. Their optical counterparts are systematically fainter than those in the Titov & Malkin (2009) compilation. Since the IVS selection process is directed at compact, milliarcsecond radio quasars, it is important to test whether their redshift distribution differs from that of the FIRST–SDSS quasar sample (Kimball et al. 2011), which is selected without regard to morphology, spectral index, or angular size, and extends to much lower flux densities.

The redshift distribution of the sources from this paper and Titov et al. (2011) is shown in Figure 5(a). For comparison, Figure 5(b) shows the distribution of 1594 point sources with known redshifts from ICRF2, using redshift data from Titov & Malkin (2009). The SuperCOSMOS Hambly et al. (2001) morphological classification was used to remove galaxies from the Titov & Malkin (2009) list, and the sample was further restricted to those with radio-optical offsets $< 1''$ and Galactic latitudes $> 10^\circ$ (A. L. Schaefer et al. 2013, in preparation).

The redshift distribution for the sources from this paper and the earlier paper (Titov et al. 2011) is completely consistent with having been drawn from the same redshift distribution as FIRST–SDSS quasars (Kimball et al. 2011), with a

Kolmogorov–Smirnov (K-S) test giving a probability $p = 0.84$ of the two samples being drawn from the same distribution. Thus the sharp drop-off that we see in the number of quasars at $z \gtrsim 2$ is a reflection of the underlying quasar distribution, and not a selection effect of the IVS candidate sources. While the K-S plot for the ICRF2 sample shows an apparent excess of low-redshift sources compared with FIRST–SDSS, the difference is not significant, with a K-S probability of $p = 0.24$. We attribute this excess to selection effects arising from the redshifts in (Titov & Malkin 2009) being drawn from the literature, and therefore likely to be biased toward brighter, lower-redshift quasars.

5. SUMMARY AND CONCLUSION

We present redshifts and spectra for 120 emission-line objects identified with radio sources from the candidate International Celestial Reference Catalog. Most of the target objects are in the south and many had not previously been optically identified. While redshifts were usually based on two or more lines, those for 22 objects were based on a single emission line, in most cases assumed to be Mg II; many of these single-line redshifts were supported by other spectral information and most are considered reliable. In addition, we classed 19 sources as probable BL Lac objects, based on a high S/N but featureless spectra. A further 18 targets were considered to have an S/N too low for confident spectral classification.

The distribution of redshifts from this paper, together with those from our earlier paper (Titov et al. 2011), is consistent with the much larger sample drawn from FIRST and SDSS (Kimball et al. 2011). This implies that the ultra-compact, flat-spectrum sources that make up the IVS Reference Catalog are not distinguished from the radio quasar population at large. On the other hand, the distribution of redshifts from the much larger sample drawn from ICRF2 (Titov & Malkin 2009) has a small, but not significant excess of low-redshift quasars, almost certainly the result of observational selection.

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2. Two Gemini Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science

Figure 4. Spectra of the five color-selected quasars from NVSS/FIRST and SDSS. Dashed lines (blue) indicate emission lines used for redshift determination; dot-dashed lines (red) indicate lines detected at a lower signal-to-noise ratio or blended. Further details are given in Table 4.

(A color version of this figure is available in the online journal.)

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3. Six meter Big Azimuthal Telescope (BTA) operated by the Special Astrophysical Observatory (Russia).

4. Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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Figure 5. (a) Distribution of redshifts among the ~ 150 IVS sources from this paper and the previous paper (Titov et al. 2011, abbreviated above as T11). The lower panel shows the cumulative redshift distribution (K-S test) compared with the FIRST-SDSS sample (Kimball et al. 2011). (b) Corresponding redshift distribution and K-S test for 1594 ICRF2 quasars from Titov & Malkin (2009); see text.

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REFERENCES

- Afanas'ev, V. L., Dodonov, S. N., Moiseev, A. V., et al. 2009, *ARep*, **53**, 287
- Arias, E. F., Charlot, P., Feissel, M., & Lestrade, J.-F. 1995, *A&A*, **303**, 604
- Becker, R. H., White, R. L., & Helfand, D. J. 1995, *ApJ*, **450**, 559
- Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, *AJ*, **115**, 1693
- de Bruijne, J. H. J. 2012, *Ap&SS*, **341**, 31
- Fey, A., Gordon, G., & Jacobs, C. (ed.) 2009, The Second realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, IERS Technical Notes 35, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main
- Hambly, N. C., Davenhall, A. C., Irwin, M. J., & MacGillivray, H. T. 2001, *MNRAS*, **326**, 1315
- Jones, D. H., Read, M. A., Saunders, W., et al. 2009, *MNRAS*, **399**, 683
- Kimball, A. E., Ivezić, Z., Wiita, P. J., & Schneider, D. P. 2011, *AJ*, **141**, 182
- Ma, C., Arias, E. F., & Eubanks, T. M. 1998, *AJ*, **116**, 516
- MacCarthy, D., & Petit, G. (ed.) 2004, IERS Conventions (2003), IERS Technical Notes 32, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main
- Mignard, F., & Klioner, S. 2012, *A&A*, **547**, A59
- Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, *A&A*, **369**, 339
- Schlüter, W., & Behrend, D. 2007, *JGeod*, **81**, 379
- Shaw, M. S., Romani, R. W., Cotter, G. H., et al. 2012, *ApJ*, **748**, 49
- Titov, O., Dickey, J. M., Lovell, J. E. J., & McCulloch, P. M. 2013, *Proc. IAG Symp. 139, Earth on the Edge: Science for a Sustainable Planet*, ed. C. Rizos & P. Willis (Berlin: Springer)
- Titov, O., Jauncey, D. L., Johnston, H. M., et al. 2011, *AJ*, **142**, 165
- Titov, O., & Malkin, Z. 2009, *A&A*, **506**, 1477
- Wampler, E. J., & Oke, J. B. 1967, *ApJ*, **148**, 695
- York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, *AJ*, **120**, 1579