Radio Spectra and Variability of Gigahertz Peaked-Spectrum Radio Sources and Candidates

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ABSTRACT

We have made long-term high radio-frequency observations of Southern and equatorial active galactic nuclei (AGNs). After complementing these data with data from the literature we have constructed the radio spectra of these sources and searched for sources with inverted spectra in the gigahertz range. We have identified 12 new sources with spectral shapes resembling those of the gigahertz peaked-spectrum (GPS) sources, and 8 other sources with inverted spectral parts in the gigahertz region. Several of these new GPS source candidates have high ($\geq$ 10 GHz) peak frequencies in the observer's frame, and they all exhibit strong long-term variability. We have also studied the variability behavior of known GPS sources, mainly quasar-type sources. All of the 14 sources included in our sample show moderate to extremely high radio variability, and at least 12 of them are variable also in the millimeter domain. Long-term monitoring of these sources shows that some of them have spectral shapes resembling those of classical variable flat-spectrum sources, indicating that some of these sources have been misidentified as GPS sources when only sparsely sampled data have been available. On the other hand, 4 of the variable sources show persistent GPS-type spectra at all stages of activity, suggesting that at least some of the GPS sources can be variable.

Subject headings: quasars: general – radio continuum

1. Introduction

Gigahertz Peaked-Spectrum (GPS) radio sources are extragalactic radio sources characterized by convex spectra peaking in the gigahertz range and steep at high radio-freqeuencies. Even though there are several other properties often coupled with the definition of a GPS source, the spectral shape is the single most important characteristic of a GPS source. A comprehensive review of the properties of GPS sources has been given by O'Dea (1998).

Most known GPS sources peak at around 1 GHz (De Vries et al. 1995). Only few known sources peak at extremely high frequencies, above 10 GHz. RXJ 0952.7+5151 and RXJ 1459.9+3337 peak at 20 and 30 GHz, respectively (Edge et al. 1996, 1998), and B1936−155 and B2008−159 both peak at $\nu_T \approx$10–20 GHz in the observer's frame (Tornikoski et al. 2000). Snellen et al. (1998a) report the source B1945+6024 peaking at a frequency higher than 15 GHz, because the highest observing frequency that their group used was 15 GHz, and the source spectrum was still inverted at that frequency.

In addition, Grainge & Edge (1998) report the detection of 50 GPS sources with extreme peak-frequencies in a survey area of 2000 square degrees. The peak-frequencies of these sources were above 10 GHz, and several of them had rising spectra at the highest observing frequency of 43 GHz. The sources included in this survey were relatively faint (a flux limit of 50 mJy at 5 GHz was used), i.e. sources that often are excluded from high-frequency studies. A fuller report of this study, or a source list, are not available yet, but the result suggests that the number of extreme-peaking GPS sources is much greater than earlier assumed. Indeed, so far the selection has mainly been made using low-frequency data only, so the population of sources that peak above ca. 10 GHz could be strongly underrepresented in the centimeter-wavelength-selected samples.

In addition to the aforementioned fact that sources relatively faint at low radio-frequencies easily are excluded from high-frequency studies, also the very low number of data points may play a role in the selection process. Selecting GPS-candidates based on one-epoch observations is problematic if the candidate is variable, because it is impossible to determine whether the source spectrum has a true GPS shape or whether the source was only observed in a very active state. In many radio loud quasars the spectrum at high radio-frequencies considerably flattens, or even gets inverted, during an outburst. Also when the GPS candidate selection for higher frequency studies is made by using catalog data with data entries possibly from more than a decade earlier than the high-frequency observation, the nonsimultaneity of observations makes it impossible to determine the true shape of the radio spectrum.

In Tornikoski et al. (2000) we suggested that many more GPS sources with extreme peak-frequencies exist, but they are easily ignored because their low-frequency data points may have been taken during a flaring state of their variability cycle, indicating flatter spectra than the typical inverted spectra of the canonical GPS sources, and especially because they are not being systematically searched for at the high radio-frequencies.

Our group has been studying AGNs at high radio-frequencies since 1987 with the Swedish–ESO Submillimeter Telescope (SEST) at the European Southern Observatory (ESO) site of La Silla, Chile, latitude 29° South. During our various observing projects we have observed both well-known strong and variable sources as well as some samples of rarely observed sources (e.g., Tornikoski et al. (1993, 1994, 1999a, 2000); details about the SEST AGN monitoring observations can be found in Tornikoski et al. (1996)). We have not made any systematic search for new GPS sources, but from our relatively well-sampled data sets complemented by data from the literature we were earlier able to identify two new GPS sources peaking at high frequencies (Tornikoski et al. 2000), and that encouraged us to thoroughly examine our complete data base in order to identify more high-peaked GPS sources and candidates among the sources observed with the SEST.

The sources currently included in the GPS source lists are very heterogeneous. Nevertheless, there are many observational characteristics often coupled with the definition of a GPS (O'Dea 1998, and references therein): 1. They are very compact, with linear sizes of <1 kpc. 2. In the radio, these sources together with the compact steep spectrum (CSS) sources are the least variable class of compact extragalactic radio sources. 3. Superluminal motion appears to be rare. 4. Optical polarizations are low ($\leq 1\%$). 5. GPS sources identified with quasars often have large redshifts.

Even though the aforementioned properties seem to be common to most GPS sources, there are counter examples for all of them (Edge et al. 1996, 1998; Snellen et al. 1995; O'Dea et al. 1991; O'Dea 1998). Thus the shape of the spectrum is the most important feature presently known that distinguishes the GPS sources from other compact extragalactic radio sources.

The spectra of GPS sources tend to be steep but fairly straight at frequencies above the peak frequency. De Vries et al. (1997) have constructed a generic GPS source spectrum based on their sample of sources peaking between 0.5 and 10 GHz. For this spectrum the optically thick spectral index is $\alpha = +0.51 \pm 0.03$ (for $S \propto \nu^{\alpha}$), and after the turnover $\alpha = -0.36 \pm 0.05$ for the flat part $\nu_T < \nu \leq 2\nu_T$ and $\alpha = -0.73 \pm 0.06$ for $\nu > 2\nu_T$.

In Section 2 we discuss the radio spectra of a set of sources and identify new GPS candidates, in Section 3 we discuss the radio variability of GPS sources and in Section 4 we discuss the properties of the GPS sources in the light of our observations.

2. Radio spectra of new GPS source candidates

In Tornikoski et al. (2000) we studied the spectra and variability of a complete sample of flat spectrum ($\alpha_{2.7GHz-5.0GHz} > -0.5$) bright ($S > 1$Jy at least once at frequencies $\nu \geq 10$GHz) sources in the Kühr 1 Jy catalog (Kühr et al. 1981) and within the declination range of $0° > \delta > -25°$. In that paper we also identified two new high-peaking quasar-type

GPS sources, B1936−155 and B2008−159.

For this paper, we wanted to study additional objects not included in Tornikoski et al. (2000). Out of our SEST data base, we have examined ∼100 sources with at least one data point at 90 GHz and/or 230 GHz with $S/N \geq 4$. Almost all of these sources are quasars or BL Lacertae objects. Many of these sources are standard targets of radio or multiwavelength monitoring and are known to exhibit strong variability and have relatively flat radio spectra. Thus it was not surprising to find a large number of sources having spectra that were very flat or even inverted in the cm–mm region, especially during outbursts. In order to discriminate against true GPS-type spectra and spectra that are inverted only during an outburst, we gathered as much cm- to mm-data as possible. We complemented our SEST data sets with the following: the Parkes Catalog (Wright & Otrupcek 1990); hereafter PKS; the Kühr 1Jy catalog (Kühr et al. 1981); hereafter K1; and the following other published data of one or several sources: Beasley et al. (1997); Bramwell (1993); Edelson (1987); Ghosh et al. (1994); Giacani & Colomb (1988); Gregorini et al. (1984); Kovalev et al. (1999); Kühr et al. (1981); Quiniento et al. (1988); Quiniento & Echave (1990); Quiniento & Cersosimo (1993); Reuter et al. (1997); Salonen et al. (1987); Steppe et al. (1992, 1993); Teräsranta et al. (1992, 1998); Tingay et al. (1997); Tornikoski et al. (1993, 1996); Veron (1996); Wright & Otrupcek (1990); UMRAO (2000). The frequency range of these data extends from ν <1 GHz to $\nu \approx 230$ GHz. The references and frequencies are listed in Table 1. For many of the sources we had several epochs of data points across the entire frequency range. The longest and best-sampled time series come from our Metsähovi and SEST observations that span for over 15 and 12 years, respectively.

In the following, we examine in more detail the sources that were found to have a clearly convex, GPS-type, spectrum (Subsection 2.1), and some other sources that seem to have an inverted spectrum, but which is flatter than the spectra of the typical GPS sources, or for which we have too little data to draw any definite conclusions about their true spectral shape (Subsection 2.2). In Table 2 and Table 3 we list these sources, respectively, together with their classification and redshift information. We use the following classification for the sources: BLO stands for BL Lacertae objects, HPQ for highly polarized quasars with a measured optical polarization p >3%, LPQ for low polarized quasars with a measured optical polarization p <3%, QSO for quasars with no polarization information available, and GAL for galaxies. For the sources in Table 2 we also list the estimated peak frequencies of their spectra, estimated from the quiescent spectra (minimum fluxes) and assuming the spectral shape of the "generic" GPS spectrum by De Vries et al. (1997), when applicable.

When studying the radio spectra of quasars and trying to determine whether the source has a GPS source spectrum or not, for example by comparing the shape to the generic GPS source spectrum presented by De Vries et al. (1997), we must bear in mind that many of these sources exhibit very strong radio variability which often flattens the shape considerably, or even turns an otherwise falling spectrum into an inverted one during an outburst. The variability will be discussed in Section 3, and in this section we will mainly concentrate on studying the minima of the measured flux densities at each frequency, i.e. the assumed quiescent spectrum. For the sources with very few data points (or, in some cases, only one-epoch data at each observing frequency) the variability behaviour is unknown and thus we can not make any conclusive statements about the true shape of their radio spectrum.

2.1. Sources with GPS-type spectra

In Fig. 1 and Fig. 2 we have plotted the radio spectra of all of the sources that exhibit GPS source -type spectra. The data for these plots are as listed in Table 1. We have left out any measurements with $S/N < 4$. The catalog data points with no error bars contained no information about the error of the measurement.

B0048−097. This is a relatively well-studied BL Lac object, with strong variability across the whole frequency range. The old catalog data from PKS & K1 seem to represent a relatively high state of the activity cycle. Even the shape of the quiescent spectrum, however, remains slightly inverted up to 10 GHz. During the outbursts the spectrum is highly inverted up to ca. 10 GHz, from where it remains relatively flat up to 90 GHz.

B0332−403. ($z = 1.445$ often quoted, but Shen et al. (1998) point out that this redshift, though widely used in the literature, may be incorrect). This source is an HPQ ($p = 14.8\%$, Impey & Tapia (1990)). This source has not been listed in the published lists of GPS sources or candidates, but based on the comment by Shimmins et al. (1971) and the generally accepted definition of a GPS, Shen et al. (1998) mention that this source could be classified as a gigahertz peaked-spectrum source. Our data confirm the GPS-nature of its spectrum, showing a spectrum that is inverted up to 5 GHz.

B0454−234. ($z = 1.003$) This is an HPQ, with an optical polarization up to p =27% (Wills et al. 1992). The source exhibits strong variability from 2 to 230 GHz. Based on only one-epoch but simultaneous observations at 1 and 3.9 GHz (Kovalev et al. 1999), the radio spectrum of this source seems to be inverted to ca. 3–4 GHz. During outbursts the spectrum is inverted all the way up to 20 GHz, but in the quiescent state the spectrum steepens after 8 GHz.

B0537−441. ($z = 0.894$) Usually classified as a BL Lac object, but also referred to as a transition object between classical BL Lac objects and quasars (Maraschi et al. 1985). The source is rapidly variable across the electromagnetic spectrum, and it is a strong variable

EGRET γ-ray source (Thompson et al. 1993; Hartman et al. 1999). The source has been proposed as a candidate for microlensing (Stickel et al. 1988; Romero et al. 1995), but the microlensing theories have also been disputed by other authors (Falomo et al. 1992; Lewis & Williams 1997). In our plot the spectrum is inverted up to ca. 5 GHz and during outbursts up to at least 10 GHz.

B1057−797. This is a relatively little observed very southern source with no data available between 8 and 90 GHz. With the currently available data the spectrum appears inverted up to at least 8 GHz. There is no polarization information available for this source and no information about its redshift.

B1334−127. ($z = 0.539$) An HPQ with p =16.1% (Kühr & Schmidt 1990). This source has been well sampled at the SEST observing frequencies and shows very strong and rapid variability at the high radio frequencies. With the currently available data set the quiescent spectrum is slightly inverted up to 20 GHz. At 90 and 230 GHz the source has been monitored very densely between 1987 and 1999, and the data set probably includes the actual extremes of the flux variation at these frequencies. Even the relatively sparse cm-data includes data points from observations taken several years apart and thus can be taken as an indication of approximately the true minima and maxima, giving the spectrum a convex shape at all times.

B1349−439. The source identification has been discussed in detail in Veron (1996). The paper shows that there are two optical sources near the radio source PKS 1349−439. PKS 1349−439 can be identified as a BL Lac object with a high and variable optical polarization (p_{max} = 21.5%, Impey & Tapia (1988)), and the other one is a radio quiet Seyfert 1 galaxy at $z = 0.052$. Veron (1996) call the source a flat spectrum radio source, but our plot, with added low-frequency varaibility data from HartRAO and high-frequency SEST data, shows that the spectrum is inverted up to 8 GHz.

B1954−388. (z = 0.626) An HPQ with p = 10.9% (Impey & Tapia 1990). This source has an inverted spectrum up to around 10 GHz. The number of 2 and 5 GHz observations is larger than that at the other low frequencies, the flux density at 2 GHz varying between 1 and 2 Jy. The catalog values for 640 MHz and 1.4 are higher than the minima at 2 GHz, but the observations are also non-simultaneous. The variability at 90 GHz is relatively strong, and the flare spectrum from approximately mid-1992 (taken at 2.3, 4.8, 8.4, 90 and 230 GHz) is strongly inverted up to 90 GHz.

B2128−123. (z = 0.499) An LPQ (p_{max} = 0.6%, Stickel et al. (1994)) with an inverted spectrum up to ca. 5 GHz and evident variability especially above 8 GHz.

B2136+141. (z = 2.427) An LPQ (p_{max} = 1.6%, Stickel et al. (1994)) with a spectrum that is slightly inverted up to 8–10 GHz in the quiescent state, and clearly inverted ($\alpha \geq +0.5$) during outbursts.

B2254−204. A BLO with high optical polarization (p = 14.3%, Impey & Tapia (1988)). The source is one of the relatively rarely observed radio sources, the spectral plot only contains radio data from PKS and our own observations (HartRAO and SEST). The current data show a spectrum that is inverted up to ca. 15–20 GHz.

B2255−282. (z = 0.926) An LPQ (p =2%, Impey & Tapia (1990)) that was the subject of a multifrequncy study in Tornikoski et al. (1999a). In 1997 this source was observed in a very active state in the millimeter domain, and later it was found to have a very bright high-energy γ-ray outburst, observed by the EGRET. The source has exhibited blazar-like variability in its active state, during which no optical polarization measurements were unfortunately made. Tornikoski et al. (1999a) noted that the radio spectrum in its quiescent state peaks above 10 GHz, and during the millimeter flare at around 90 GHz. In Fig. 2f we reproduce the data plot with some additional post-flare data points.

2.2. Other sources with inverted spectra

In Fig. 3 and Fig. 4 we have plotted the radio spectra of all of the sources that have a somewhat inverted spectrum, but most of which show highly inverted spectra only during flares and are otherwise relatively flat, or which lack data to determine the true shape of the spectrum. The data for these plots are as listed in Table 1.

B0252−549. ($z = 0.537$) A rarely observed source with no polarization information available. Our spectrum consists of only 7 data points, taken at 6 different frequencies. Thus no variability information is available and the frequency coverage is sparse. The plot shows a spectrum that is moderately inverted from 2.7 to 90 GHz, but the low-frequency part of the spectrum is flat rather than inverted, and the inverted shape of the high-frequency part may be due to variability only.

B0402−362. ($z = 1.417$) An LPQ ($p = 0.6\%$, Impey & Tapia (1990)) that shows very strong variability in the millimeter-domain but for which no low-frequency variability information have been published. Our plot shows a spectrum that is initially flat but strongly inverted from 2 to 8 GHz. The strong variability in the millimeter domain leads us to suspect that the true quiescent spectrum of this source might be flat, and get inverted only during flares.

B0539−057. ($z = 0.839$) This source is an HPQ with $p = 4.5\%$ (Stickel et al. 1994). The variabilty apparent in the 8 GHz data and the lack of variability information at the other frequencies prevent us from determing the exact peak frequency, with the current data it can only be estimated to be between 5 and 20 GHz.

B1145−071. ($z = 1.342$) This source was among the first discovered real binary quasars, and the very first binary where one quasar is radio bright, and the other one is radio faint (Djorgovski et al. 1987). Our radio spectrum is inverted up to 5 GHz. The source exhibits variability at least in the cm region. The 5 GHz data were obtained during two epochs only, whereas the 8 GHz data set spans over 18 years of time, and thus the flux minima at 5 GHz may not represent the true quiescent state. The source probably is a variable source with a flat spectrum that gets inverted during outbursts.

B1546+027. ($z = 0.413$) An HPQ with strong and rapid polarization variations ($p_{max} = 13\%$, Smith et al. (1994)) and also in the radio domain a highly variable source with an inverted spectrum up to the GHz region in the quiescent state, and up to at least 20 GHz in the flaring state. The high frequency part of the radio spectrum remains extremely flat also in the quiescent state ($\alpha \approx -0.3$).

B2145+067. ($z = 0.990$) An LPQ with $p = 1.03$ (Wills et al. 1992). The spectral shape is flat up to 5 GHz, after which it is inverted up to ca. 20 GHz. The source exhibits very strong variability, but the spectral shape after 5 GHz remains constant from the low to the high state.

B2216−038. ($z = 0.901$) An LPQ ($p_{max} = 1.2\%$, Stickel et al. (1994)) with an inverted spectrum between 1 and 8 GHz, and variablity observed across the radio spectrum.

B2243−123. ($z = 0.630$) An HPQ ($p_{max} = 5\%$, Stickel et al. (1994)) with a slightly inverted spectrum up to 5 GHz. If the best sampled 8 GHz monitoring data, 61 data points spanning from 1981 to 1999, represent the true variability also at the other, much more sparsely sampled, frequencies, this source is only a flat-spectrum source with relatively high variability.

In addition to the aforementioned sources with inverted spectra, there are several sources with very flat spectra that get inverted during outbursts: B0109+224, B0306+102, B0754+100, B0823+033, B1144−379, B1244−255, B2121+053. When studying the flare spectra only, or in many cases even the average spectra, these spectra show convex, GPS-like shapes. But our data base with years of variability data shows that calling these sources GPS sources would be an over-interpretation based on too sparse data. The variability issue is addressed in more detail in Section 3.

3. Variability of GPS sources

A common feature for almost all of the sources introduced in Section 2 is strong variabilty across the radio spectrum and especially in the millimeter domain.

Earlier it has been argued that GPS-type sources have very low radio variability. On the other hand, the high radio-frequency variability of GPS sources has not been studied very much. In Tornikoski et al. (2000) we showed that the millimeter domain variability of the two bona fide GPS sources, B0238−084 and B0743−006 is about as strong as that of the other typical flat-spectrum quasars. The two newly identified GPS sources, B1936−155 and B2008−159, also showed strong variability. Variability of some other GPS sources has also been confirmed by Edge et al. (1996, 1998). It has been proposed, however, that the possible variabilty in GPS sources should be coherent across the spectrum, whereas the variability in ordinary flat-spectrum sources, caused by components peaking at different frequencies, is likely not to occur coherently across the whole spectrum (Snellen et al. 1995, 1998b).

Because at least some of the GPS sources seem to exhibit such strong variability in the millimeter domain, we also wanted to study the variability of the known GPS sources, and also to see whether variable sources may have been misidentified as GPS sources when only sprasely sampled spectra have been available for the identification. For example the source B0109+224 from our original SEST sample has a spectrum that is completely flat up to 230 GHz in the quiescent state, and highly inverted ($\alpha \geq +0.5$) up to 40 GHz in the flaring state. If only a very limited number of data points are available, this kind of a highly variable source is easily (mis-)classified as a GPS source. As mentioned at the end of Section 2, our sample consists of several sources with spectra similar to that of B0109+224, i.e. flat in the quiescent state, and inverted during outbursts.

In Table 4 we list all of the known GPS sources (including some GPS source candidates) that have been observed at SEST by our group, together with their flux information at 90 and 230 GHz. In the following we discuss their radio spectra in more detail, excluding the sources already discussed in Tornikoski et al. (2000) and the CSS source B1151−348. The radio spectra of the sources discussed here are plotted in Fig. 5 and Fig. 6.

B0440−003 = NRAO 190. ($z = 0.844$) An HPQ ($p_{max} = 12.5\%$, Stickel et al. (1994)) that is identified as a GPS candidate in Stanghellini et al. (1998), with ν_T=0.3 GHz. Our plot shows a highly variable spectrum peaking at $\sim$2 GHz.

B0511−220 ($z = 1.296$) A quasar with an unknown optical polarization that is listed as a GPS source candidate in Dallacasa (1998), with $\nu_T \approx$5 GHz. Our data confirm the

GPS-shape of the spectrum.

B0528−250. (z = 2.779) An LPQ (p_{max} = 0.7%, Stickel et al. (1994)). This source is listed as a GPS source in De Vries et al. (1997) and O'Dea (1998), with ν_T=1.4 GHz. Our SEST observations have all been non-detections ($S/N < 4$), in Table 4 the upper limits only are given for this source at 90 and 230 GHz. This indicates that the optically thin part of the spectrum falls very steeply. Our data plot for this source does not reveal any truly inverted shape in the spectrum above 1 GHz, and since the low-frequency part of the spectrum seems to be flat and variable, we suggest that this source should not be classified as a GPS source.

B0528+134. (z = 2.067) An LPQ (p_{max} = 0%, Stickel et al. (1994)) that was identified as a GPS candidate in Stanghellini et al. (1998), with ν_T=1.9 GHz. Due to its status as a flaring gamma-ray source (Hunter et al. 1993; Mukherjee et al. 1996; Boettcher & Collmar 1998; Zhang et al. 1998; Mukherjee et al. 1999) this source has been a target of several multifrequency campaigns and it has been under extensive flux monitoring during the recent years. It shows high variability in the cm- and mm-domains. If we study the quiescent spectrum, i.e. the minimum flux densities at each frequency, we notice that the spectrum is very flat all the way to ca. 40 GHz, but inverted only between 0.4 and 1 GHz, where only very limited number of data points are available. During outbursts the spectrum is extremely inverted.

B1127−145. (z = 1.187) An LPQ with p_{max} = 1.2% (Stickel et al. 1994). This source has been listed as a GPS source in Stanghellini et al. (1998) and O'Dea (1998), with ν_T=1 GHz. Our spectral plot shows a falling spectrum after 1.4 GHz, with notable variability. The data points taken at HartRAO in 1991–1992 at 2.3 and 4.8 GHz show much lower flux densities than the values given in PKS and K1. The relatively high state of the PKS and K1 data probably explains why this source has been classified as a GPS source. We believe that also the 1.4 GHz PKS and K1 data points show the spectrum in a flaring state, which means that the general spectral shape after 1 GHz is falling and the source should not be classified as a GPS source.

B1519−273. A BLO with unknown redshift and high optical polarization ($p_{max} = 11.4\%$, Impey & Tapia (1988, 1990)). This source is listed as a bona fide GPS source in De Vries et al. (1995), with ν_T=5 GHz. Our plot shows a relatively flat quiescent spectrum that is inverted during flares.

B1718−649. ($z = 0.014$) This source was identified as the nearest GHz peaked-spectrum radio galaxy in Tingay et al. (1997), with ν_T=3 GHz. Some variability is observed in the hig-frequency flux measurements, but with the current data sets the spectrum has a characteristic convex shape, peaking near 3 GHz. The VLBI observations in Tingay et al. (1997) also confirm the GPS nature of this source.

B2126−158. ($z = 3.266$) An LPQ with $p_{max} = 1.5\%$ (Stickel et al. 1994). This source was classified as a GPS source in De Vries et al. (1997); Stanghellini et al. (1998); O'Dea (1998), with ν_T=4 GHz. Our plot shows a flat spectrum that steepens after 8 GHz in the quiescent state but remains flatter in the flaring state. The quoted ν_T=4 GHz is probably an over-interpretation based on only PKS and K1 catalog data.

B2134+004. ($z = 1.932$) An LPQ with $p_{max} = 2.3\%$ (Stickel et al. 1994). This source has been identified as a GPS source in Stanghellini et al. (1998) and O'Dea (1998), with $\nu_T \approx$5 GHz. Our plot shows an extremely beautiful example of a convex spectrum, peaking between 5 and 8 GHz. The source exhibits some variability, but the spectral shape remains an extraodrinarily pronounced GHz peaked-spectrum in spite of the variations.

B2230+114, CTA 102. ($z = 1.037$) An HPQ with $p_{max} = 10.9\%$ (Stickel et al. 1994). This source has been classified as a GPS source candidate in Stanghellini et al. (1998), with ν_T=0.5 GHz. In our plot the quiescent spectrum is steadily falling (with $\alpha \approx -0.5$) after 0.4 GHz. This source is well known for its rapid and strong radio variability, sometimes connected to optical variations (Tornikoski 1999b), and the extremely high variability is evident from our data plot also. The 327 MHz data points from Ghosh et al. (1994) confirm also the low-frequency domain variability, leading us to suggest that the steepening seen between 180 and 410 MHz is due to sparsely sampled, non-simultaneous data instead of the actual average/quiescent spectrum of the source.

4. Discussion

We have presented radio spectra for 12 sources that we call new quasar-type GPS source candidates, having quiescent spectra with an inverted shape, peaking at frequencies ν_T >1 GHz. 6 of these sources have extremely high peak frequencies, $\nu_T \geq$10 GHz in the observer's frame. In addition to these 12 sources we have presented a set of 8 other sources with inverted parts in their spectra, but either having too flat spectra for actual GPS sources or being too poorly sampled to determine whether they are GPS candidates. All of the 12+8 sources for which we have multi-epoch data exhibit high variability.

We calculated the spectral index from 90 to 230 GHz for our 12 GPS candidate sources. For the two sources for which either the 90 GHz or the 230 GHz data were unavailable, we used the 150 GHz data point from the IRAM data instead. The median spectral index between 90 and 230 GHz for both the quiescent as well as the average spectra of these sources is $\alpha = -0.63$, the quiescent spectral indices ranging from $\alpha = -0.20$ to $\alpha = -1.17$. The "generic" high-frequency spectral index presented by De Vries et al. (1997) for GPS sources was $\alpha = -0.73$, only a little steeper than our sample median. For the complete sample of southern AGNs in Tornikoski et al. (2000) the median quiescent spectral index between 90 and 230 GHz was $\alpha = -0.74$, i.e. not greatly different from that of the present sample. During flares the turnonver frequencies can be shifted to as high as 100 GHz, but for most of the sources the 100–230 GHz spectral indices remain almost constant from the quiescent to the flaring state, the median 90 to 230 GHz spectral index in the flaring state being $\alpha = -0.60$.

The redshifts of the new GPS candidate sources range from 0.5 to 2.4, with only one having a redshift of z =2.4, and the others having redshifts of z <1.5. There is no redshift information available for 4 sources. 6 out of the 12 GPS candidates are reported to have optical polarizations p >3%, some as high as p >20%, 3 sources have a low optical polarization p <3%, and for additional 3 sources no optical polarization information was available. There are no significant correlations between the turnover frequency, optical polarization, redshift and the spectral steepness. The variability of these sources does not seem to directly correlate with the turnover frequency or any other property, but the correlation is difficult to verify because the data sets are very inhomogeneous (different amounts of data, different frequency coverages, non-simultaneous data taking, etc.)

In addition to the strong variability, many of our sources also show other characteristics usually considered to be more typical to the blazar-type sources: high optical polarization, strong and variable multiwavelength emission, high-energy γ-ray flares, etc.

Our group has also made millimeter observations of a sample of 14 sources identified as GPS sources in the literature. Many of these "bona fide" GPS sources are highly variable, and several of them seem to be variable, flat-spectrum sources that have been misidentified as GPS sources due to too sparse data sampling. In Marecki et al. (1999) the authors argue that because most of the known GPS sources show hardly any variability, sources that show variability should probably not be called GPS sources. Our data show that sources with persistent GPS-type spectra at all stages of activity (e.g., B0238−084 and B0743−006, presented in Tornikoski et al. (2000), and 0511−220 and B2134+004, discussed in Section 3) can be variable up to the millimeter domain. In O'Dea (1998) the linear sizes of B0743−006 and B2134+004 are given as 0.036 kpc and 0.017 kpc, respectively, which shows that these sources are also extremely compact and thus "typical" GPS sources. Even though we have shown the risks of using sparsely sampled data to make GPS identifications, we also suggest that at least some of the quasar-type GPS sources are indeed highly variable.

In the light of our data sets it seems evident that there are two main classes of peaked-spectrum qusars: 1) the variable flat-spectrum sources that have a clearly inverted spectrum only during outbursts; and 2) the variable inverted-spectrum sources whose spectral shapes remain inverted at all stages of activity and which thus adhere to the definition of the genuine GPS sources. The present complete samples of GPS/CSS sources should be redefined to avoid the inclusion of sources where several components (e.g., core, jet, consecutive shocks) may contribute to the shape of the spectrum.

In our present sample there are no non-variable quasar-type peaked-spectrum sources, but this may be due to the selection effect of having only studied sources that had been included in our monitoring campaigns, known or supposed to be variable and thus "interesting". However, there have been no systematic long-term studies of the radio-to-millimeter variability of the complete sample of quasar-type GPS sources, so it is possible that they all can exhibit moderate to high variability. Dedicated variability studies across the radio spectrum are needed in order to determine whether variability actually is typical for the quasar-type GPS sources, as well as to determine which sources are variable, flat-spectrum sources showing inverted spectra only at some stage of activity or when only non-simultaneous data are available, and which have gigahertz-peaked spectra at all times.

Several sources in our sample have high peak frequencies. Even though sources peaking anywhere above 1 GHz are by the classical definition GPS sources, it is possible that these moderate-redshift, bright, variable sources with spectral peaks well above 1 GHz (many even above 10 GHz in the observer's frame, 20–40 GHz in the rest frame) are fundamentally very different from the "original" GPS sources. Even though the maximum frequency of the spectral peaks of the known GPS sources to date seems to be around 20 GHz in the observer's frame, we can not rule out the possibility that even higher peak frequencies could exist. Both VLBI and IR/optical images as well as multifrequency variability data will be needed to determine whether the low-peaked, high-peaked, and possible ultra-extreme-peaked GPS sources belong to the same class of objects, maybe presenting a continuity of properties from one extreme to the other, or whether the low-peaked and high-peaked sources form two (or more) very different classes of objects.

Because most high-frequency radio observing campaigns are based on selections made at low radio-frequencies, the actual number of extreme-peaked quasars may be much higher than currently known. Sources that have catalog data points only fainter than 0.5 Jy at 2.3 or 5 GHz have extremely rarely been observed at the higher frequencies. For extreme peak-frequencies in the 20–40 GHz range, fainter sources with S <0.5 Jy at 5 GHz could show flux levels as high as 1–1.5 Jy at the peak-frequency, assuming the canonical GPS spectrum, and still much higher, assuming a more steeply rising spectrum like the one predicted by the homogenous self-absorbed synchrotron source model. It is important to investigate whether there is such a population of undetected extreme-peaking sources faint in the low-frequency domain. Our group is in the process of conducting a study of such fainter sources.

5. Conclusions

We have presented a set of radio spectra based on our group's long term high radio-frequency (90 and 230 GHz) observations with the SEST, complemented with data from the literature. We have identified 12 quasar-type sources with convex spectra resembling those of the GPS sources and peaking at high frequencies. 6/12, i.e. 50%, of the sources have their spectral turnover at $\nu_T \geq 10$ GHz in the observer's frame, which makes them unusually high-peaked sources. We also present 8 additional sources with inverted spectra in the GHz region but either with too little data to make conclusive statement about their true spectral shape or with spectral shapes, though at least somewhat inverted, not strictly adhering to the generic GPS shape. Probably at least some of these sources are only flat-spectrum sources that are variable and for which the often sparsely sampled data were taken during a relatively active state.

It is not clear whether the low-peaked and high-peaked GPS sources belong to the same class of objects, maybe presenting a continuity of properties from one extreme to the other, or whether they form two very different classes of objects, showing only similar spectral shapes. It is possible that the number of these extreme peaked-spectrum sources is much higher than earlier assumed, and that the small number of currently known such sources is mainly due to the fact that no search for them has been conducted at high radio-frequencies. To study these sources in more detail and to determine the true number of such sources one needs data sets with dense temporal sampling to exclude the sources with spectra flattened by an outburst.

The variability of the new high-peaked sources as well as that of the earlier known GPS sources observed by our group is strong, thus the often quoted statement that GPS sources would belong to the least variable class of compact extragalactic radio sources seems to be incorrect for these qusar-type GPS sources. On the other hand, the strong variability of flat-spectrum radio sources may also lead to misidentifications. We have shown 6 cases where the densely sampled radio spectrum of the sources quoted as GPS sources in the literature is in conflict with the generally accepted definition of a GPS source spectrum. If the variable sources are observed only few times, the source may have been in an active state during the observation and showing an unusually flat, or even inverted, spectrum. With dense long-term monitoring it is possible to observe the actual flux density minima and maxima, and thus determine the overall shape of the source spectrum.

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Fig. 1.— New sources with GPS-type spectra. a) B0048−097, b) B0332−403, c) B0454−234, d) B0537−441, e) B1057−797, f) B1334−127.

Fig. 2.— New sources with GPS-type spectra, continued. a) B1349−439, b) B1954−388, c) B2128−123, d) B2136+141, e) B2254−204, f) B2255−282.

Fig. 3.— Other sources with inverted spectra. a) B0252−549, b) B0402−362, c) B0539−057, d) B1145−071.

Fig. 4.— Other sources with inverted spectra, continued. a) B1546+027, b) B2145+067, c) B2216−038, d) B2243−123.

Fig. 5.— Radio spectra of bona fide GPS sources and GPS candidates. a) B0440−003, b) B0511−220, c) B0528−250, d) B0528+134, e) B1127−145, f) B1519−273.

Fig. 6.— Radio spectra of bona fide GPS sources, continued. a) B1718−649, b) B2126−158, c) B2134+004, d) B2230+114.

Table 1. Source of data for Fig.1–6.

Reference	Frequency (GHz)	Site	Epoch	Notes
Beasley et al. (1997)	89, 147	SEST	1996.4	
Bramwell (1993)	2.3, 4.8, 8.4	HartRAO	1991–1993	
Edelson (1987)	20, 110	OVRO	1986.43, 1987.32	
Ghosh et al. (1994)	0.327	OSRT	1985–1988	
Giacani & Colomb (1988)	1.41	IAR	1985.2–1987.1	
Gregorini et al. (1984)	0.408	Bologna Nothern Cross	1981.8	
Kovalev et al. (1999)	0.96, 2.3, 3.9, 7.7, 11.2, 22	RATAN-600	1997.9–1998.0	
Kühr et al. (1981)	0.1–90	various	1960–1988	
Quiniento et al. (1988)	1.410	IAR	1983–1988	
Quiniento & Echave (1990)	1.410	IAR	1983–1990	
Quiniento & Cersosimo (1993)	1.410	IAR	1983–1993	
Reuter et al. (1997)	90, 142, 230	IRAM	1993–1994	
Salonen et al. (1987)	12, 22, 37	Metsähovi	1980–1985.5	
Steppe et al. (1992)	90, 150, 230	IRAM	1987.3–1990.9	
Steppe et al. (1993)	90, 150, 230	IRAM	1990.9–1993.0	
Teräsranta et al. (1992)	22, 37, 87	Metsähovi	1985.5–1990.5	
Teräsranta et al. (1998)	22, 37, 87	Metsähovi	1990.5–1995.5	
Tingay et al. (1997)	0.408–230	various	various	1
Tornikoski et al. (1993)	2.3, 4.8, 8.4	HartRAO	1991.0–1991.7	
	22, 43	Itapetinga	1988.1–1990.9	
	90, 230	SEST	1988.3–1992.0	
Tornikoski et al. (1996)	90, 230	SEST	1987.8–1994.5	
Tornikoski et al., this paper	90, 230	SEST	1994.5–1999.8	
Veron (1996)	2.7–8.9	various	various	2
Wright & Otrupcek (1990)	0.080–22	various	various	

[1]Data only for PKS 1718−649.

[2]Data only for PKS 1349−439, data collected from the literature.

Table 2. New sources with GPS-type spectra

Source	Class.	z	ν_T (GHz)	p_{max} (%)
B0048−097	BLO	?	10	?
B0332−403	HPQ	1.445	5	14.8
B0454−234	HPQ	1.003	3	27
B0537−441	BLO	0.894	5	?
B1057−797	QSO	?	10	?
B1334−127	HPQ	0.539	20	16.1
B1349−439	BLO	?	8	21.5
B1954−388	HPQ	0.626	20	10.9
B2128−123	LPQ	0.499	5	0.6
B2136+141	LPQ	2.427	8	1.6
B2254−204	BLO	?	15	14.3
B2255−282	LPQ	0.926	20	2

Table 3. Other sources with inverted spectra

Source	Class.	z	p_{max} (%)
B0252−549	QSO	0.537	?
B0402−362	LPQ	1.417	0.6
B0539−057	HPQ	0.839	4.5
B1145−071	QSO	1.342	?
B1546+027	HPQ	0.413	13
B2145+067	LPQ	0.990	1.0
B2216−038	LPQ	0.901	1.2
B2243−123	HPQ	0.630	1.2

Table 4. Known GPS sources and candidates observed at SEST.

Source	Class.	z	$S_{min}(90)$ (Jy)	$S_{max}(90)$ (Jy)	$S_{ave}(90)$ (Jy)	$N_{obs}(90)$	$S_{min}(230)$ (Jy)	$S_{max}(230)$ (Jy)	$S_{ave}(230)$ (Jy)	$N_{obs}(230)$	Ref.
0238-084	GAL	0.005	1.00	2.32	1.53	23	0.19	0.89	0.64	12	1
0440-003	HPQ	0.844	0.43	1.23	0.69	23	0.16	0.78	0.38	12	3
0511-220	QSO	1.296	0.26	0.45	0.37	3	0.19	0.24	0.21	4	7
0528-250	LPQ	2.779		< 0.20		4		< 0.16		7	1,5
0528+134	LPQ	2.067	2.17	8.00	5.22	43	0.83	4.46	3.04	27	3
0743-006	LPQ	0.994	0.37	0.76	0.48	8	0.15	0.15	0.15	1	1,2,4,5
1127-145	LPQ	1.187	0.66	2.15	1.33	13	0.62	1.30	0.85	11	2,4
1151-348	GAL	0.258				0	0.09	0.09	0.09	1	6(CSS)
1519-273	BLO	?	0.52	0.88	0.68	7	0.22	0.44	0.34	7	1
1718-649	GAL	0.014	0.59	1.30	0.77	8	0.23	0.31	0.27	5	8
1936-155	HPQ	1.657	0.55	1.49	1.03	15	0.21	0.85	0.39	10	9
2008-159	LPQ	1.657	0.32	1.60	1.10	19	0.14	0.71	0.40	9	9
2126-158	LPQ	3.266	0.29	0.29	0.29	1	0.15	0.15	0.15	1	1,2,4,5
2134+004	LPQ	1.932	0.78	2.18	1.73	29	0.28	0.75	0.61	17	2,4
2230+114	HPQ	1.037	1.55	8.33	4.25	31	0.59	4.89	1.82	14	3

[1] De Vries et al. (1997), Table 2.

[2] Stanghellini et al. (1998), Table 1.

[3] Stanghellini et al. (1998), Table 2.

[4] O'Dea (1998), Table 1.

[5] O'Dea (1998), Table 7, GPS.

[6] O'Dea (1998), Table 7, compact steep-spectrum (CSS) source.

[7] Dallacasa (1998)

[8] Tingay et al. (1997)

[9] Tornikoski et al. (2000)