

# Multi-frequency Study of Intraday Variable Sources

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**Abstract.** Intraday variability (IDV) of compact extragalactic radio sources is a complex phenomenon and shows a wavelength dependent mixture of refractive interstellar scintillation (RISS) (dominant at long cm-wavelengths) and source-intrinsic effects (dominant at shorter wavelengths). Detailed investigations of individual sources and new high frequency observations suggest a source-intrinsic contribution to the IDV pattern at least in some sources. However, the sizes of intraday variable sources at cm-wavelength are typically smaller than the scattering size set by the ISM in our galaxy and scintillation must be present, too.

We present new IDV observations in different regimes (from cm to sub-mm wavelengths) and show how such multi-frequency study can be used as powerful instrument to describe different aspects of IDV.

## 1. Introduction

Variability of flat-spectrum quasars on timescales of weeks to years provides a powerful tool to study the inner regions of these objects. Variability on shorter timescales, less than one day, was discovered in the mid eighties (Witzel et al. 1986, Heeschen et al. 1987). It was found (Quirrenbach et al. 1992) that about 30% of all compact flat-spectrum sources show such intraday variability (IDV). The observed rapid variations imply, via the light travel time argument, a very small source size and a very high apparent brightness temperature (of up to  $10^{21}$  K), if we consider these variations as intrinsic.

To prevent the Compton catastrophe (which limits the brightness temperature to  $\leq 10^{12}$  K), IDV would require relativistic boosting with Doppler-factors of up to  $D = 1000$ . This is much higher than observed with VLBI. Qian et al. (1991, 1996) proposed a modified shock-in-jet model, which uses a special geometry to prevent such high Doppler-factors. In this model, a thin shock moves relativistically along an oscillating jet. The observed brightness temperature  $T_B^{obs}$  then scales with the 5<sup>th</sup> power of the intrinsic Lorentz factor and only moderate Doppler factors ( $D \leq 60$ ) are needed. It, however, appears unlikely to apply for more than a few special objects, for which furthermore a ‘suspicious’ geometrical fine tuning between shock thickness and orientation of the jet axis relative to the line of sight is required (Beckert et al. 2002).

On the other hand, the sizes of intraday variable sources at cm-wavelengths are typically smaller than the scattering size set by the Interstellar Medium (ISM) in our galaxy. Hence, IDV sources are small and should show refractive interstellar scintillation (RISS). While the variations in sources like 0917+62 can be explained mainly by RISS (cf. Rickett et al. 1995), this explanation clearly fails in other sources like e.g. 0716+71 (cf. Wagner & Witzel, 1995), where correlated radio-optical IDV is present and most recently IDV at 9 mm has been detected (Krichbaum et al 2002). At least in two sources, the evidence for RISS being the main cause for rapid variability has recently be-

come very strong: 0405–385 (Jauncey et al. 2000) and J1819+3845 (Dennett-Thorpe & de Bruyn 2002). A similar behavior was also proposed for 0917+624 (Rickett et al. 2001, Jauncey & Macquart 2001), but finally was not confirmed by observations with the 100m radio telescope in Effelsberg (Fuhrmann et al. 2002). Observations at sub-millimeter wavelengths are important, since they help to disentangle between extrinsic (dominant at longer cm-wavelengths) and intrinsic (dominant at mm/optical-bands) causes of the variability.

## 2. Observations and Data Reduction

### 2.1. cm-wavelengths:

All measurements were done with cross scans using the 100m radio telescope of the Max-Planck-Institut für Radioastronomie (MPIfR) in Effelsberg. Our data (Tab.1) consist of a complete sample of high declination ( $\delta > 55^\circ$ ) flat-spectrum ( $\alpha > 0.5$ , we use:  $S \propto \nu^{-\alpha}$ ) radio sources extracted by the 1Jy catalog (Kühr et al. 1981). Here, a new set of observations (carried out in March 2000) is included. Besides the total power, linear polarization information is collected: the incoming radiation is split in left- and right components of circular polarization. These signals enter in a polarimeter that provide as output the Stokes parameters: I, Q, U.

The data reduction was performed using CONT2, a task of the standard software package TOOLBOX of the MPIfR. Observations of non-variable sources assured a reliable flux density calibration (accuracy  $\sim 0.5\%$ ) allowing to correct for instrumental and atmospheric effects (for details, see Quirrenbach et al. 1992). Description of the data and summary of the experiments (since 1989 up to 1999) are given in Kraus et al. (submitted).

## 3. Statistical analysis

Statistics provides a basis to investigate the occurrence of the rapid variations in compact objects. Main instrument

**Table 1.** List of the complete sample of flat-spectrum sources at high declination. We also report: galactic latitudes, optical identifications, known redshifts (Stickel et al. 1994) and the spectral indices evaluated between 11 and 6 cm. *Last column:* IDV type (at 6 cm) from observations (see below in the text).

Name	$b_{II}$	ID	$z$	$\alpha_{11/6}$	Type
0016+73	+10.7	QSO	1.781	.16	I
0153+74	+12.4	QSO	2.338	-.32	0
0212+73	+12.0	BL	2.367	-.12	0
0454+84	+24.7	BL	0.122	.38	II
0602+67	+20.9	EF	-	.39	II
0615+82	+26.0	QSO	0.710	-.03	0
0716+71	+28.0	BL	-	.21	II
0723+67	+28.4	QSO	0.846	-.33	0
0831+55	+36.6	GAL	0.241	-.46	0
0833+58	+36.6	QSO	2.101	1.31	0
0836+71	+34.4	QSO	2.172	-.33	0
0850+58	+38.9	QSO	1.322	.78	II
0917+62	+41.0	QSO	1.446	.25	0
0945+66	+41.9	EF	-	-.46	0
0954+55	+47.9	QSO	0.901	-.12	0
0954+65	+43.1	BL	0.367	.25	II
1031+56	+51.9	QSO	0.459	-.31	0
1039+81	+34.7	QSO	1.254	.40	II
1150+81	+35.8	QSO	1.250	-.09	I
1418+54	+58.3	BL	0.152	.24	II
1435+63	+49.7	QSO	2.068	-.23	I
1637+57	+40.4	QSO	0.750	.56	II
1642+69	+36.6	QSO	0.751	-.26	II
1739+52	+31.7	QSO	1.379	.07	II
1749+70	+30.7	BL	0.770	-.33	I
1803+78	+29.1	BL	0.684	.26	I
1807+69	+29.2	GAL	0.051	-.35	II
1823+56	+26.1	BL	0.664	.17	I
1928+73	+23.5	QSO	0.302	-.01	0
1954+51	+11.8	QSO	1.230	-.14	II
2007+77	+22.7	BL	0.342	.67	I
2021+61	+13.8	GAL	0.227	.10	0

for such analysis is the *modulation index*:

$$m[\%] = 100 \cdot \frac{\sigma_S}{\langle S \rangle}$$

(where  $\langle S \rangle$  is the mean flux density and  $\sigma_S$  is the rms flux density variations.) We define also the *variability amplitude*:

$$Y[\%] = 3\sqrt{m^2 - m_0^2}$$

to compare observations taken at different epochs and frequencies ( $m_0$  is the modulation index of a non-variable source).

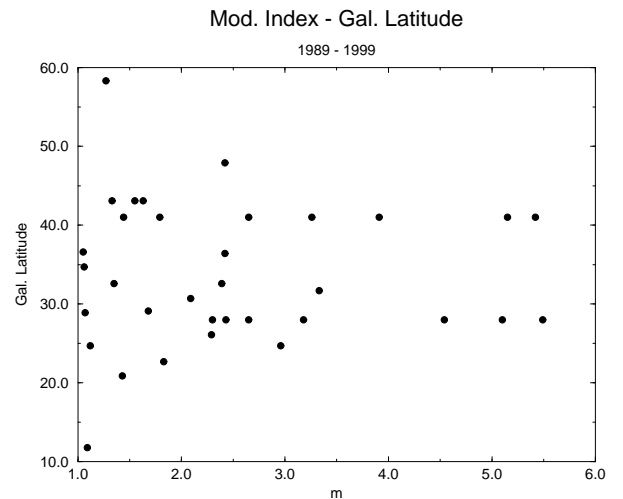
Following Simonetti et al. (1985), we define the first order *Structure Function*,  $SF$ :

$$D(\tau) = \langle (S(t) - S(t - \tau))^2 \rangle_t.$$

This function provides typical timescales and periodicity of variations and depending on its shape we can define the IDV type of the objects: a monotonic increase in the

SF defines a Type I source. If the SF shows a maximum then fast variations are present (Type II). Type 0 denotes non-variable sources. The last column of tab.1 indicates the IDV types (at 6 cm) in our sample. One can evaluate the modulation index from the autocorrelation function as shown in Beckert et al. (this conference). These authors relate SF to observable parameters assuming some constraints for the ISM and for the source structure.

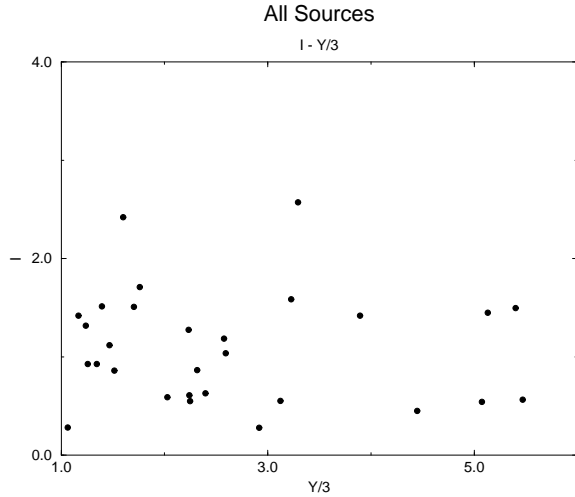
Comparing recent measurements to previous similar data (Quirrenbach et al. 1992), we immediately see that some objects changed their IDV characteristics. About one third of the sources in the complete sample showed variations of type II and overall two thirds can be considered type I or type II. However, these fractions are consistent with previous analysis (Heeschen et al. 1987, Quirrenbach et al. 1992). Fig.1 shows the modulation indices of all the variable (type I and II) sources plotted versus galactic latitude  $b^{II}$ . (Most of our sources are in the range



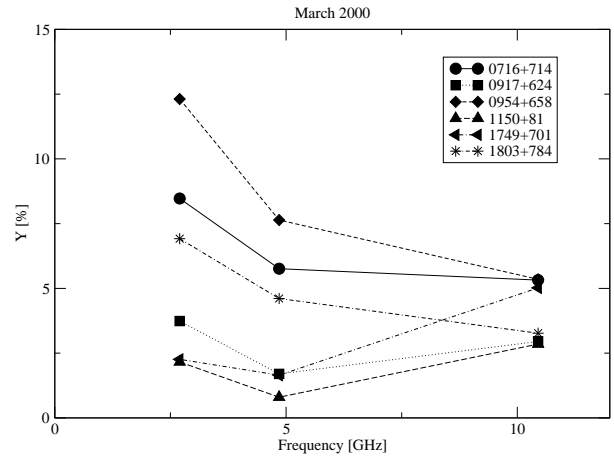
**Fig. 1.** Modulation indices and galactic latitude (summary of all epochs).

$20 \leq b^{II} \leq 50$ .) No correlation between variations and  $b^{II}$  was observed at any given epoch. No dependence of the variability amplitudes on the mean flux density of the sources can be seen, either (fig.2).

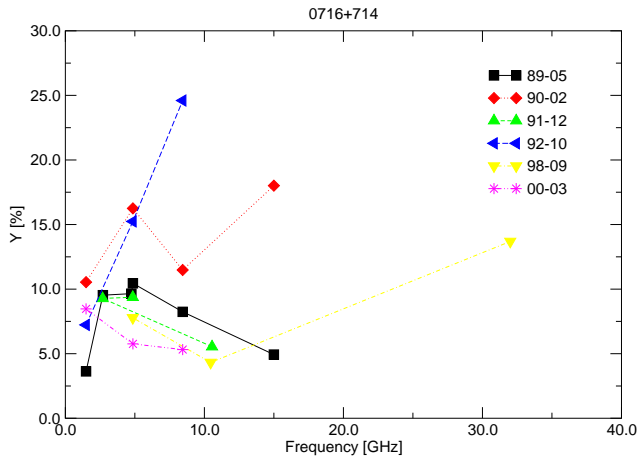
Scattering theory predicts two regimes of refractive interstellar scintillation: weak and strong. A change between strong and weak occurs around 3–8 GHz (Walker 1998): below a critical frequency the scattering is strong. Such frequency can be determined observing variations at different frequencies. Fig.3 shows the variability behavior of 0716+714 for 6 different epochs. Immediately we note various patterns indicating changes either in the source structure or in the interstellar medium. In some case we see an increase of the variability amplitudes at high frequency. This is not in agreement with the expectations from RISS, unless one takes a source intrinsic and time variable contribution into account, which increasingly dominates towards higher frequencies. Fig.4 shows the behavior of dif-



**Fig. 2.** Variability amplitudes at 6 cm against mean flux densities (summary of all epochs).



**Fig. 4.** Variability amplitudes against frequency during March 2000 for the variable sources.



**Fig. 3.** Variability amplitudes against frequency at different epochs.

ferent sources in March 2000. Again, in some sources  $Y$  increases with  $\nu$ .

Occurrence of IDV may show dependence on redshift (considered as compactness indicator). Moreover, differences could occur in time scales or in the magnitude of the variability in BL Lacs and Quasars. Yet, no evidences for such correlations came out of our analysis.

#### 4. Sub-Millimeter Observations

In January 2002, a combined total power and polarization experiment (in collaboration with the MPIfR Bolometer group) was carried out at the Heinrich Hertz Sub-Millimeter Telescope (HHT, a Steward Observatory facility) using the MPIfR 19-channel bolometer array (at 345 GHz). Furthermore, in April/May 2002 a radio-sub-millimeter-optical campaign was carried out. The sub-mm data were taken with the 19-channel bolometer at the HHT with the on-off technic. Both set of data were

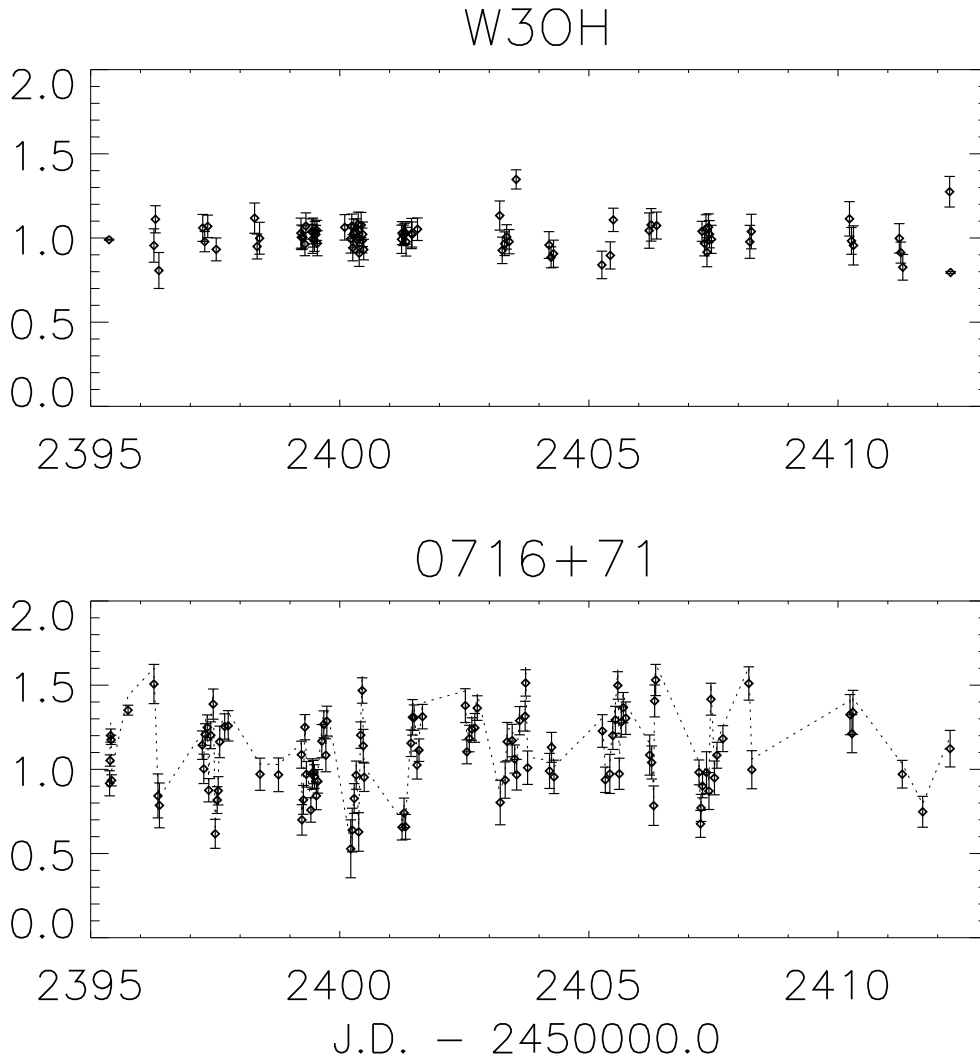
reduced using the program NIC (which is part of the Gildas software package and is mainly developed at IRAM Grenoble). The data were corrected for the atmosphere opacity ( $\tau$ ) using SKYDIP scans that measure  $\tau_{\text{zenith}}$ . Strong and compact objects (Ultra Compact HII regions, planetary nebula and planets) provide a overall calibration accuracy of  $\sim 10\%$ .

A first and encouraging result is the tentative detection of intraday variations in the total flux density of the BLLac object 0716+714. For this source, after each scan a calibrator was observed and a SKYDIP was done. First data analysis indicates 50% variations with a time scale  $\sim 0.5$  days (fig.5). Assuming a lower limit for the redshift of 0.3, such variations imply  $T_B \simeq 2.2 \times 10^{14}$  K and a Doppler factor,  $D \simeq 6$ .

Radio-optical correlation seen earlier in 0716+714 and the new detected sub-millimeter IDV (if confirmed). will rule out the RISS as sole explanation for the rapid variations in this source.

#### 5. Conclusions

Even 15 years after its discovery, Intraday Variability in flat-spectrum radio sources remains a hot and controversial topic in astronomy and still asks for an explanation. In the last decade a lot of effort was spent trying to disentangle the different mechanisms responsible for the observed rapid variations. The statistical analysis presented here does not give definitive evidences for one of the proposed models: source-intrinsic or propagation effects. Flat spectrum radio sources are strongly variable on longer time scales. Fuhrmann et al. (2002) claim strongly quenched scattering to explain the change in the variability pattern in 0917+62 (Kraus et al. 1999). Hence changes in the source morphology and scattering can be strictly related: variability can show different characteristics at different epochs due to changes in the apparent source size. Multi-frequency observations constrain the refractive scintilla-



**Fig. 5.** Preliminary results at 345 GHz. Tentative detection of IDV in 0716+714 compared to the calibrator W3(OH).

tion theory and can be combined with VLBI observations to put some constraints to the ISM structure or the intrinsic source sizes.

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