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# The Impact of Interstellar Scintillation on Astrometric VLBI

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**Abstract**

We review the evidence demonstrating that interstellar scintillation (ISS) is the principal mechanism responsible for the intra-day variability (IDV) seen at cm wavelengths in many compact, flat-spectrum extragalactic radio sources. The presence of ISS in a radio source implies the presence of microarcsecond structure in the source. We examine the implications of such compact structure, and suggest that these ultra-compact radio scintillators may form a significant part of the next generation International Celestial Reference Frame (ICRF) sources because of their high level of compactness and positional stability.

## 1. Introduction

Over the last five years considerable evidence has accumulated to demonstrate unequivocally that ISS is the principal cause of the IDV seen at cm wavelengths in many compact, flat-spectrum extragalactic sources. Much of this evidence has come about through the discovery of three very rapidly varying IDV sources, PKS B0405−385 [1], J1819+3845 [2] and PKS B1257−385 [3]. The flux density of these sources changes so rapidly at 5 to 8 GHz that many *scints* of the quasi-periodic variations can be seen in a single 12-hour track.

The variability in these sources is sufficiently rapid that changes of 50% to 100% take place in time scales of an hour or less. This has allowed the detection of a significant time delay between the patterns of variability seen at widely separated radio telescopes. The first measured time delay was for PKS B0405−385 where, despite the poor geometry, a time delay of several minutes was measured at 4.8 and 8.6 GHz between the variability patterns seen at the VLA and the ATCA [4]. With more favourable geometry, Dennett-Thorpe & de Bruyn [5] tracked J1819+3845 with the VLA and Westerbork and saw not only a significant time delay, but were able to watch it change with the rotation of the Earth. Most recently, successful time delay measurements have been made at 4.8 and 8.6 GHz at several epochs for the rapid variable source PKS B1257−326 [6]. Such time delay measurements are only feasible for these extremely rapid variables. For these sources the observations of such a time delay establishes unequivocally an ISS origin for their rapid IDV.

The presence of time delays of order minutes implies a velocity of the interstellar medium (ISM) of order 30-40 km$s^{-1}$ which is close to the speed of the Earth in its annual orbit around the sun. This coincidence implies the presence of an *annual cycle* in the variability characteristics of an IDV source if ISS is the mechanism responsible for the IDV. When the Earth is moving in the same direction as the ISM the relative speed is small and the variations will be slow. Six months later the Earth is moving in the opposite direction to the ISM, the relative speed is high and the variations will be much more rapid. This annual cycle, in the form of Earth Orbit Synthesis, is proving to be a powerful analysis tool for determining radio source structure at micro-arc-second resolution [7].

Such annual cycles have been found for a number of sources, B0917+624 [8] [9], PKS B1519−273 [10], and J1819+3845 [11], and it looks as though such behaviour may be widespread. The beautiful pattern of the annual cycle can be seen for the rapidly variable source PKS B1257−326 as determined by Bignall et al., [3]. Most recently an analysis of the 5 years of 2.3 GHz VLBI flux density measurements [12] derived from the Keystone Project [13] has revealed a strong annual cycle in the ITRF and ICRF source B0059+581 [16]. Despite large, overall flux density changes B0059+581 has repeatedly exhibited an annual cycle, firmly establishing an ISS origin for the IDV. B0059+581 was also found to exhibit ISS at 4.8 GHz in the recent MASIV VLA Survey [14].

The presence of such measured time delays and the presence of annual cycles in IDV sources establishes unequivocally that ISS is the principal cause of the IDV seen in many compact, flat-spectrum radio sources at cm wavelengths.

As is the case for optical scintillation in the atmosphere where *stars twinkle and planets do not*, interstellar scintillation at cm wavelengths selects those sources which house the most compact components which have microarcsecond sizes [15]. These scintillators are thus amongst the most compact known AGN, which is a good starting point for them to be high quality position reference sources.

## 2. The MASIV Survey: Finding More Scintillators

The number of known scintillators is small, however. We are therefore undertaking a large-scale, Micro-Arcsecond Scintillation-Induced Variability, MASIV, VLA survey of the northern sky at 4.9 GHz. Our objective is to construct a sample of 100 to 150 scintillating extragalactic sources with which to examine the microarcsecond structure and the parent populations of these sources and to probe the turbulent interstellar medium causing the scintillation. The first epoch of observations revealed variability on timescales ranging from hours to days in 85 of 710 compact flat-spectrum sources. The number of highly variable sources, those with rms flux density variations greater than 4% of the mean, increases with decreasing source flux density.

We have also completed follow-up 8.4 GHz VLBA observations of 75 low flux density scintillators from the first two epochs of the MASIV survey [17]. With these plus the existing data from the USNO radio reference frame image database, we can compare the milliarcsecond structures of the MASIV scintillators and non-scintillators. One striking point we find using several statistical measures, is that the scintillators are significantly more core-dominated than the non-scintillators. We find at 8.4 GHz with the VLBA [18] that 19 of the 75 low flux density scintillators are unresolved at a dynamic range of typically 200:1.

## 3. Are the Scintillators Good Radio Reference Frame Sources?

In order to be included in the radio reference frame a source should be strong at cm wavelengths, should be a point source with little or no structure at mas resolution, and its position should be stable on the sky.

With the advent of the Mark 5 VLBI recording systems with Gb$s^{-1}$ data rates coming into widespread operation, the first criterion should be relatively easily satisfied by sources with flux densities in excess of $\sim$ 100 mJy. There are plenty of MASIV scintillators above 100 mJy.

The need for point sources is perhaps the most difficult criterion to fulfill. The presence of ISS demonstrates that the scintillators possess micro-arc-second components and are thus amongst the most compact known AGN. Our 8.4 GHz VLBA observations [17] [18] reveal that amongst flat-spectrum AGN, the scintillators are significantly more core-dominated. We find that 49% of the scintillators have in excess of 80% of their flux density in the core, compared with 10% of the non-scintillators. It is important to note that the scintillators and non-scintillators in our study were drawn from populations with identical spectral index distributions, so the only selection criterion separating the two classes is the presence or absence of scintillation.

Structural stability is a prime requirement for reference frame sources. While it is not possible to predict if any source will or will not be stable in the future, in many cases their past stability can be assessed. For example, B0059+581, which as noted above was found to be a strong, long lived scintillator, as was confirmed in MASIV, has weak mas structure. However, this structure has shown no variations over the 7 years that this source has been imaged in the Radio Reference Frame Image Database.

As might be expected B0059+581 also exhibits remarkable positional stability. In the analysis to select the most stable compact extragalactic sources, Feissel-Vernier [19] notes B0059+581 as one of the more stable reference frame sources. If we compare the class of MASIV scintillators with the class of ICRF defining sources for positional stability, based on the Feissel-Vernier data we find 67% of the scintillators have a positional stability index of 1 or 2, compared with 55% of the ICRF defining sources. We note that the defining sources have been preselected over a decade of VLBI observations. The scintillators as a class, on the other hand, with no selection criterion other than their scintillation, possess the better positional stability.

There are, however, a number of potential positional stability problems that might be expected with the scintillators as reference frame sources. For example, as the micro-arc-second component scintillates the flux density variability may produce position shifts due to refraction in the ISM. Such effects should be no more than the few micro-arc-seconds of the scattered component sizes. In addition, position shifts may be expected from the scintillation from possible *Christmas Tree* effects. While the scintillators are extremely compact at the milli-arc-second level, this may produce significant displacements depending on the overall milliarcsecond structure. These may be measurable and efforts should be made to do so.

## 4. Conclusions

In conclusion, we suggest that the IVS discuss selecting the additional sources for the next generation ICRF sources from the population of MASIV scintillating sources [20]. These sources possess a high level of compactness and positional stability. As such this makes them a potentially powerful population of sources to use to extend and improve the ICRF.

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