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EVIDENCE FOR REFRACTIVE SCINTILLATION OF TWO EXTRAGALACTIC SOURCES SEEN THROUGH THE GALACTIC DISK

BRIAN DENNISON,[1] R. FIEDLER,[2] K. J. JOHNSTON, J. H. SPENCER, AND E. B. WALTMAN
E. O. Hulburt Center for Space Research, Naval Research Laboratory

AND

P. E. ANGERHOFER, D. R. FLORKOWSKI, F. J. JOSTIES, W. J. KLEPCZYNSKI, D. D. MCCARTHY, AND D. N. MATSAKIS
United States Naval Observatory
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ABSTRACT

Extragalactic radio sources observed as part of a joint program between the US Naval Observatory and the Naval Research Laboratory were qualitatively examined to determine if there are any cases in which apparent variations at 2.7 GHz are uncorrelated with variations at 8.1 GHz, as might be expected for extrinsically induced refractive scintillation. Two sources exhibiting this behavior were identified, NRAO 150 and 2013+370, both of which happen to lie within 2° of the Galactic plane. The calculated refractive scintillation properties, based on intrinsic VLBI sizes and scattering measurements in the Galactic disk, are in reasonable agreement with the observed fluctuations. We therefore interpret the light curves of these sources as significantly affected by refractive scintillation in the interstellar medium. Our findings suggest that extragalactic sources seen through extended paths in the Galactic disk may be modulated by refractive scintillation even at gigahertz frequencies.

Subject headings: interstellar: matter — radio sources: general

I. INTRODUCTION

Recently, it has been suggested that radio waves from a sufficiently compact source can be refractively focused by large-scale ($\sim 10^{14}$ cm) irregularities in the interstellar medium (Shapirovskaya 1978; Rickett, Coles, and Bourgois 1984). Typical interstellar velocities, of order 100 km s^{-1}, would then transport the pattern of randomly focused and defocused regions in the observer's plane, resulting in slow, or refractive, scintillation (as contrasted to fast, or diffractive, scintillation caused by much smaller irregularities). In the model proposed by Rickett *et al.*, the large-scale irregularities responsible are part of the same spectrum of turbulence as the small-scale irregularities that give rise to the well-known diffractive scintillation phenomena. The power spectrum of the density irregularities is of the form (Rickett 1977)

$$P(q) = C_n^2 q^{-\alpha} , \qquad (1)$$

where q is the spatial wavenumber and α is most likely in the range $3.7 < \alpha < 4.3$ (Goodman and Narayan 1985). The coefficient C_n^2 specifies the strength of turbulence in the medium.

The model of Rickett *et al.* predicts that the dominant linear scale for refraction is approximately that of the scattering disk. Current evidence supporting this model includes apparent long-term fluctuations in pulsar fluxes (Helfand, Fowler, and Kuhlman 1977), the correlation between the observed time scales and dispersion measure (Sieber 1982), and apparent drifts of pulsar diffractive scintillation patterns—presumably caused by refraction of ray paths (Hewish 1980).

Of considerable importance is the effect refractive scintillation has on compact extragalactic source observations. The available scattering data (Cordes, Ananthakrishnan, and Dennison 1984) suggest that at high Galactic latitudes the effect may be important at frequencies below 1 GHz. Hence it is quite important to determine the extent to which refractive scintillation may be responsible for the well-known low-frequency variability phenomenon.

Considerably greater scattering is known to occur along lines of sight passing close to the Galactic plane (Dennison *et al.* 1984; Rao and Ananthakrishnan 1984; Cordes, Weisberg, and Boriakoff 1985). Apparently, this is due to a population of "clouds" residing in the Galactic disk, which, in this discussion, is taken to extend 75 pc above and below the plane. Compact sources seen through long paths (> 1 kpc) in the disk might well display apparent sizes dominated by scattering and therefore may be expected to scintillate refractively, even at GHz frequencies (Rickett 1986).

In this paper we report on a search for the effects of refractive scintillation in the radio light curves of the extragalactic sources monitored with the Green Bank interferometer at 2.7 and 8.1 GHz (Waltman *et al.* 1986).

II. DISCUSSION

Intrinsic fluctuations at 2.7 and 8.1 GHz are generally correlated, usually exhibiting a delayed and diminished amplitude at the lower frequency (Altschuler and Wardle 1976). Refractive scintillation, however, should manifest itself at (usually low) frequencies at which the scattering size is significant in comparison with the intrinsic size. The time scale is expected to scale in proportion to the apparent source size (which is a convolution of the intrinsic structure with the scattering disk). In seeking sources possibly affected by refractive scintillation, the light curves of 27 extragalactic sources in the monitoring program were qualitatively examined to see if there are any cases in which variations occurring at 2.7 GHz are uncor-

[1] Also Department of Physics, Virginia Polytechnic Institute and State University.
[2] NRC/NRL Cooperative Research Associate.

related with variations at 8.1 GHz. Two such sources, NRAO 150 (0355+508) and 2013+370, were identified, independently of their Galactic coordinates. Significantly, these are the only two extragalactic sources in the sample that lie within 3° of the Galactic plane. The sample of sources examined is distributed approximately isotropically over the sky. (Although both NRAO 150 and 2013+370 are heavily obscured, their radio spectra and VLBI morphology are generally taken to indicate that these objects are extragalactic, as will be assumed here. See Phillips and Shaffer 1983; Geldzahler, Shaffer, and Kuhr 1984.)

a) NRAO 150 ($l = 150\overset{\circ}{.}4, b = -1\overset{\circ}{.}6$)

Both light curves (Fig. 1) exhibit a long-term decline over the 7 yr monitoring period. In addition, there are significant, 5% rms fluctuations on a 1 yr time scale in the 2.7 GHz light curve. These fluctuations, which lack a comparable counterpart at 8.1 GHz, make this source remarkable.

The long-term decline, apparent at both frequencies, appears to be the aftermath of a major flare that peaked in early 1977 (Mutel and Phillips 1980; Aller *et al.* 1985). By 1983, the fluxes at both frequencies returned to the preflare levels (Dent and Kapitzky 1976; Altschuler and Wardle 1976; Aller *et al.* 1985). The spectral index was slightly inverted prior to 1982 and relatively flat thereafter (apart from relatively minor fluctuations caused by the shorter term, 1 yr, fluctuations at 2.7 GHz). Evidently, this change was caused by a transition from opaque to transparent emission in the evolving component. This, coupled with the spectra obtained during and just after the flare peak, strongly indicates that the downward trend at both frequencies is intrinsic and caused by an evolving synchrotron component injected sometime around 1977.0. Also, the reported visibility changes between 1974 and 1979, at 1.67 GHz on the NRAO–OVRO baseline (Mutel and Phillips 1980), are clearly due to an enhancement of the unresolved flux, which we interpret as due to the injected component.

The 1 yr fluctuations at 2.7 GHz are probably not intrinsic. Were they intrinsic and due to evolving synchrotron components, then we would expect to see corresponding fluctuations at 8.1 GHz, having greater amplitudes and peaking at somewhat earlier times. This is not observed. We therefore interpret the 1 yr fluctuations at 2.7 GHz as due to refractive scintillation. As we now show, this interpretation is consistent with the intrinsic source size at 2.7 GHz and the degree of scattering expected along the line of sight.

VLBI studies suggest a three-component structure for NRAO 150 (Mutel and Phillips 1980; Phillips and Shaffer 1983). At 2.7 GHz the emission is evidently dominated by a component about 7 mas in size. Since there is no convincing evidence that any of the components are blurred by interstellar scattering (at frequencies above 1.7 GHz), the degree of scattering must be inferred from the scintillation properties of pulsars seen at low Galactic latitude, and in the same Galactic longitude range as NRAO 150. The pulsars 0329+54 and 0355+54, which have relatively small angular separations from NRAO 150, have measurements of the mean level of turbulence $\langle C_n^2 \rangle$ along their lines of sight. Converting the published $\langle C_n^2 \rangle$ values (Cordes, Weisberg, and Boriakoff 1985) to an effective angular scattering size (Cordes, Ananthakrishnan, and Dennison 1984) for an extragalactic source seen through a somewhat greater path length in the disk (assumed to be 3 kpc; see below), we arrive at estimates of 0.12 mas and 0.8 mas for the scattering angle at 2.7 GHz. The apparent discrepancy results from different $\langle C_n^2 \rangle$ values for the two pulsars. The higher value (attributable to pulsar 0355+54) appears to be more representative when other low-latitude pulsars at similar longitudes are examined and is adopted here. (0329+54 has the lowest $\langle C_n^2 \rangle$ value of any low Galactic latitude pulsar in the comprehensive list published by Cordes, Weisberg, and Boriakoff 1985.)

The expected refractive scintillation index m and time scale τ, corrected for spatial filtering by intrinsic source structure, can be estimated using the following relations given by Rickett (1986) for the case in which $\alpha = 4$:

$$
\begin{aligned}
m &= m_R\,\theta_S(\theta_S^2 + \theta_I^2)^{-0.5}\,, \\
\tau &= L(\theta_S^2 + \theta_I^2)^{0.5}/1.7v\,,
\end{aligned}
\tag{2}
$$

where θ_S is the scattering angle, θ_I is the intrinsic source size, and m_R is the unquenched scintillation index (i.e., that ascribable to a point source), conservatively estimated to be 0.5 from long-term pulsar fluctuations (Rickett 1986). The path length in the medium L can be satisfactorily taken to be the path length through the disk region in which heavy scattering occurs (Dennison *et al.* 1984; Cordes, Weisberg, and Boriakoff 1985), which for NRAO 150 we estimate to be $\sim$3 kpc. At that distance and longitude (150°), the relative velocity transverse to the line of sight, due to Galactic rotation, should be $\sim$40 km s^{-1}. Including Earth's orbital motion, we adopt 50 km s^{-1} for the effective transverse speed of the medium relative to the line of sight. We then find $m \approx 0.06$ and $\tau \approx 1$ yr. Clearly, these estimates are in quite good agreement with the observed fluctuations (Fig. 1*a* and Table 1), especially given the uncertainties in the various parameters such as L and v.

At 8.1 GHz the flux is probably about evenly divided between the 7 mas component dominant at 2.7 GHz and several submilliarcsecond components dominant above 10 GHz (Kellermann *et al.* 1977). Because the scattering angle is expected to be only $\sim$0.07 mas at this frequency, only the submilliarcsecond components would effectively scintillate. Using the component sizes given by Kellermann *et al.* (1977), we find that most of the scintillating flux would be ascribable

TABLE 1

FLUCTUATION PROPERTIES OF NRAO 150 AND 2013+370

						CALCULATED		OBSERVED	
SOURCE	L (kpc)	v (km s^{-1})	ν (GHz)	θ_S (mas)	θ_I (mas)	m	τ	m	τ
NRAO 150	3	50	2.7	0.8	7	0.06	1 yr	0.05	1 yr
			8.1	0.07	0.3	0.04	20 days	<0.05	>10 days
2013+370	3.5	100	2.7	5	0.5	0.5	0.5 yr	0.05	>1 yr
			8.1	0.5	0.5	0.34	25 days	0.14	50 days

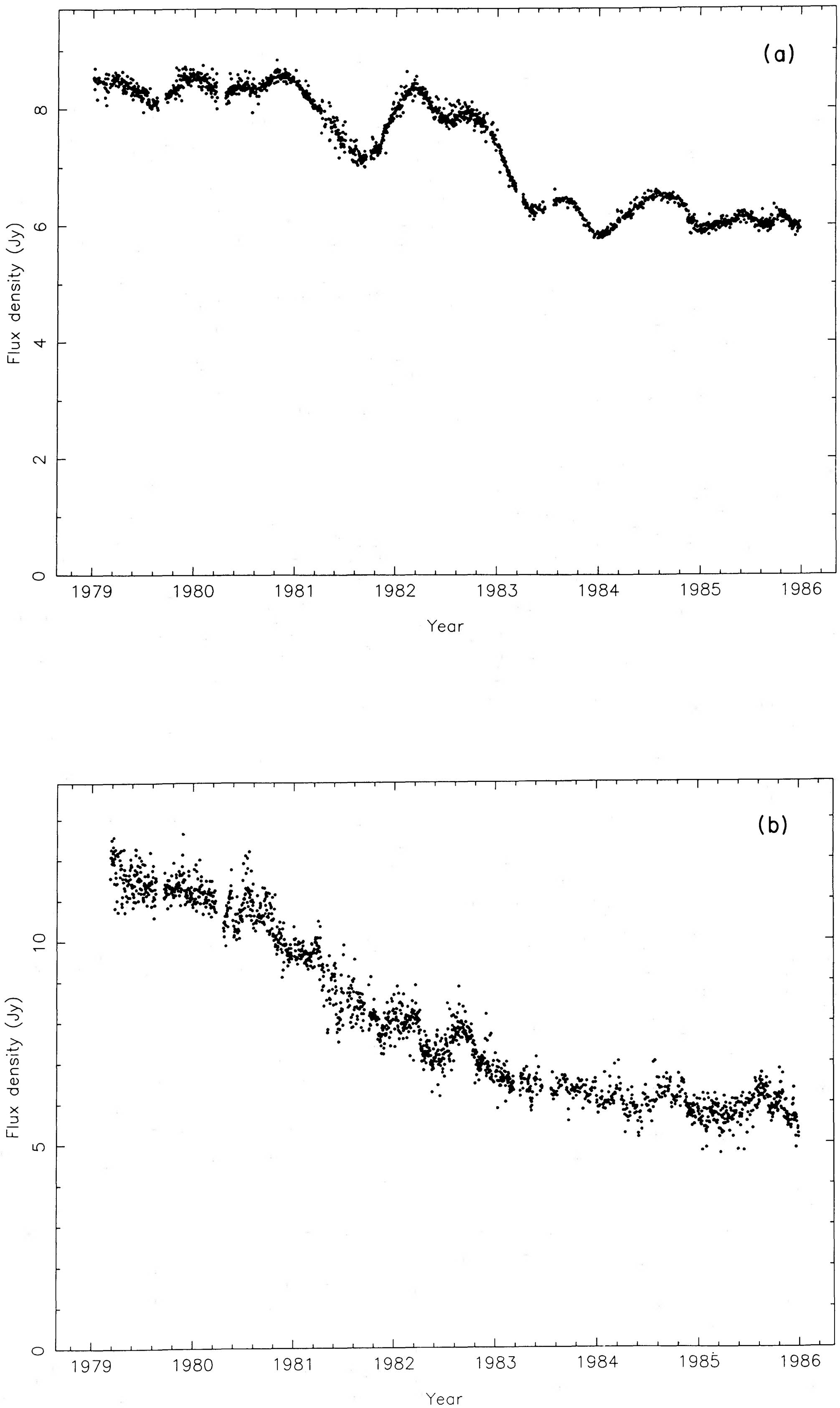

FIG. 1.—Light curves of NRAO 150 at (*a*) 2.7 GHz and (*b*) 8.1 GHz. The rms scatter at the sampling rate of 1 day, which is due to instrumental noise, is 0.12 Jy at 2.7 GHz and 0.38 Jy at 8.1 GHz.

to the dominant, and smallest (0.3 mas), component. Allowing for approximately 2:1 dilution of the scintillating flux by the larger components, we estimate that $m \approx 0.04$ and $\tau \approx 20$ days at 8.1 GHz. This estimate is somewhat less than the observed rms fluctuation about the long-term trend (Fig. 1*a* and Table 1), much of which is probably due to noise. Hence, it appears that any 8.1 GHz scintillations are at or below the noise level (although a few events, for example at 1982.7 and 1984.8, appear simultaneously with fluctuations at 2.7 GHz).

At low frequencies, the scintillation properties are somewhat harder to predict, as we lack information concerning the apparent angular size. If the ~ 20 mas component reported at 1.67 GHz (Mutel and Phillips 1980) dominates at 0.4 GHz, then we would expect $m \approx 0.47$ and $\tau \approx 10$ yr. However, this is probably incompatible with the observed lack of apparent variability at this frequency over a 5 yr time period (Fanti *et al.* 1981). If the 0.4 GHz flux is dominated by a component of size 100 mas or larger, then the lack of apparent low-frequency variability is probably compatible with the longer time scale and smaller modulation expected. Perley (1982) has reported the presence of an extended ($\sim$arcsec) component at 1.4 GHz. Its relative contribution to the 0.4 GHz flux is unknown. Yet another uncertainty concerns the frequency dependence of m_R. (See § III.)

Since refractive scintillation is to first order polarization-independent, we would not expect to observe significant correlated polarization variability. Indeed, this appears to be the case. The linear polarization did not appear to vary significantly at either 2.7 or 8.1 GHz during the earlier monitoring program of Altschuler and Wardle (1976). Aller *et al.* (1985) reported significant polarization variations at 8.0 and 14.5 GHz. However, at their lowest frequency (4.8 GHz), the variations were significantly smaller in amplitude and do not appear to be correlated with the 1 yr fluctuations we see at 2.7 GHz.

b) 2013+370 ($l = 74\overset{\circ}{.}9, b = 1\overset{\circ}{.}2$)

The light curves at 2.7 and 8.1 GHz were published by Geldzahler, Shaffer, and Kuhr (1984). At 8.1 GHz the variations are strong and rapid with a time scale of 50 days, whereas at 2.7 GHz the flux varied independently, showing a mild variation over a longer 1 yr time scale. The complete absence of any 2.7 GHz variations correlated with the strong, rapid fluctuations observed at 8.1 GHz is quite remarkable. Generally, strong intrinsic variations at 8.1 GHz are expected to be accompanied by noticeable correlated variations at 2.7 GHz, as is the case among the other variable sources in the program.

This source is intrinsically highly compact. The VLBI observations reported by Shaffer *et al.* (1978) and Geldzahler, Shaffer, and Kuhr (1984) at 10.6 GHz reveal that most of the flux originates in a (core) component, 0.5 mas in size. The remainder of the single-dish flux is found in two similarly small components which are roughly aligned with the core. At lower frequencies, the apparent size appears to be dominated by the effects of interstellar scattering, since it scales in proportion to λ^2 between 0.6 and 5 GHz (Spangler *et al.* 1986). At 1.66 GHz the apparent angular diameter is 15 mas (Spangler *et al.* 1986). This amount of scattering is in excellent agreement with the 17 mas expected at 1.66 GHz, from the level of turbulence in the direction of the pulsar, 1946+35 (Cordes, Weisberg, and Boriakoff 1985), which is only 6° away in the sky.

Because interstellar scattering is known to be quite strong, and probably dominant at frequencies below 8 GHz, and because of the above mentioned unusual variability properties, we interpret the observed variations as largely due to refractive scintillation. Rickett (1986) has also suggested the same for this source. Since, in this case, the scattering magnitude is known, it is quite straightforward to estimate the expected magnitude and time scale of refractive scintillation. Somewhat uncertain are values of L and v. At the Galactic latitude of 2013+370, the line of sight through the Galactic disk is ~ 3.5 kpc. At this distance the transverse velocity of Galactic gas (relative to the Sun) is ~ 100 km s^{-1}. Using these estimates and the above values for θ_S and θ_I, we find (equation [1])

$$m = 0.5 \text{ and } \tau = 0.5 \text{ yr at } 2.7 \text{ GHz},$$

$$m = 0.34 \text{ and } \tau = 25 \text{ days at } 8.1 \text{ GHz},$$

which is in reasonable agreement with the observed fluctuation properties (Table 1). Because the scattering disk is comparable to or exceeds the intrinsic size, the modulation is expected to be quite strong. As Spangler *et al.* (1986) suggested, it is also possible that much of the observed scattering occurs in the vicinity of the supernova remnant G74.9+1.2, which is at a distance of at least 12 kpc. The appropriate relative transverse velocity would probably be ~ 220 km s^{-1}. Such parameters yield time scales which are $\sim 50\%$ longer than those estimated above. The observed time scales appear to be about a factor of 2 longer than the above estimates, a result which is certainly consistent given the uncertainties in L and v. It may be significant that the observed ratio of the time scales at the two frequencies appears to be in good agreement with that implied by the known scattering and intrinsic source sizes. It should be noted that the observed modulation at 2.7 GHz is certainly less than the 0.5 estimated. However, as the observations span only one fluctuation event (lasting ~ 1 yr), the observed modulation must be taken as a lower limit to the actual value.

It is noteworthy that Spangler *et al.* (1986) report evidence that the scattering disk of 2013+370 may appear asymmetric at 1.66 GHz, as might be expected if the flux is significantly modulated by refraction. Confirmation of this effect is important.

III. CONCLUSIONS

Two sources in the monitoring program using the Green Bank interferometer were identified as having qualitative variability properties that may be indicative of refractive scintillation. These are the only extragalactic sources in the program seen close enough to the Galactic plane ($b < 3°$) to have their path lengths through the Galactic disk long enough (>1 kpc) that enhanced diffractive scattering is likely. In the model proposed by Rickett, Coles, and Bourgois (1984), the degree of diffractive scattering can be used to infer the effective angular scale for refractive scintillation. For NRAO 150 the scintillation properties of pulsars seen through the Galactic disk provide an indication of the degree of scattering expected along the line of sight. The other source, 2013+370, has an apparent angular size which is dominated by scattering at frequencies below ~ 8 GHz, and thus the expected refractive scintillation properties can be inferred directly. In both cases, the calculated refractive scintillation properties are reasonably consistent with the observed fluctuations. (See Table 1.) The fluctuation magnitude of 2013+370 at 2.7 GHz is considerably less than that calculated, however. This may be a result of the limited time span of the monitoring, which in this case does not exceed the time scale of a single fluctuation. Further monitoring at 2.7 GHz is required. Should the long-term fluctuation then a rethinking of the model may be in order, as the apparent angular size of this source is almost certainly dominated by diffractive scattering at this frequency. Paticularly important may be the frequency dependence of m_R, as predicted in some models (e.g., an irregularity spectrum with $\alpha < 4$, Rickett, Coles, and Bourgois 1984; Blandford and Narayan 1985, Goodman and Narayan 1985). Although pulsar observations do not appear to confirm the expected decrease of m_R with decreasing frequency (Helfand, Fowler, and Kuhlman 1977), these pulsars, having low to moderate dispersion measures, do not probe the disk region of heavy scattering particularly well. Such considerations may also be relevant to the lack of apparent low-frequency variability in NRAO 150. In this case, however, a good low-frequency VLBI map is needed.

Our findings support the refractive scintillation hypothesis as applied to compact extragalactic sources. Evidently, this mechanism is effective at GHz frequencies for at least some extragalactic sources seen through the Galactic disk, where enhanced scattering is known to occur. In these two cases, the effective scale for refraction appears to be on the order of the scattering disk (as the model predicts). This connection between diffractive scattering (caused by irregularities of scale $10^{8.4}$ cm, in the case of 2013+370) and refraction (caused by irregularities of scale $10^{14.4}$ cm), if verified in a large number of cases, would clearly demonstrate one of the model's most fundamental features, that both effects are caused by the same turbulent spectrum acting on widely different scales.

Extragalactic sources seen at high Galactic latitude experience considerably less scattering, and therefore refractive effects are expected to be strongest at frequencies below 1 GHz. Our findings tend to support the view that refractive scintillation is a cause of some observed low-frequency variability.

It should be noted that our qualitative criterion for identifying refractive scintillation (§ II) is not unique, nor is it adequate to identify all cases in which observable refractive scintillation may be present.

As stated in § II, both NRAO 150 and 2013+370 possess submilliarcsecond structure and are therefore almost certainly intrinsically variable as well. In the case of NRAO 150, we feel that we were able to separately identify some of the intrinsic variability, as discussed. Fortunately, intrinsic and extrinsic variations have rather different properties, so that in some cases at least, the presence of one, or the other, or both, can be inferred.

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P. E. ANGERHOFER, D. R. FLORKOWSKI, F. J. JOSTIES, W. J. KLEPCZYNSKI, D. D. MCCARTHY, and D. N. MATSAKIS: United States Naval Observatory, Washington, DC 20390

BRIAN DENNISON: Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

R. FIEDLER, K. J. JOHNSTON, J. H. SPENCER, and E. B. WALTMAN: Code 4130, Naval Research Laboratory, Washington, DC 20375-5000