Probing the Solar Plasma With *Mariner* Radio Metric Data, Preliminary Results

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A radio technique, exploiting the opposite changes of group and phase velocity in a dynamic plasma, was used to probe the solar corona during the superior conjunctions of the Mariner VI *and* VII *spacecraft. From an analysis of range and doppler radio metric data generated by the DSN in tracking the spacecraft, it was possible to establish a correspondence between plasma fluctuations in the radio raypath and McMath sunspot regions on the solar surface. Estimates of 3000 electrons/cm^3 and scale sizes of 6×10^4 and 2×10^6 km were made for plasma clouds transiting the radio path when tracking within a few degrees of the sun.*

I. Introduction

Shortly after their encounters with Mars in the summer of 1969, the *Mariner VI* and *VII* spacecraft entered an extended mission phase to take advantage of the continuing spacecraft life. With the advent of the *Mariner* Mars 1969 extended mission came a new ranging system, called fast acquisition ranging, using a sequential binary code (Ref. 1). This new system possesses 40 times the sensitivity of the ranging system used during the primary *Mariner* Mars 1969 mission. The increased sensitivity made it possible for the *Mariner VI* and *VII* spacecraft to be ranged around their entire orbit, particularly at 2.6 AU at their solar superior conjunctions. The range and doppler radio metric tracking close to the sun made it possible to measure the solar plasma dynamics.

The plasma dynamics were measured with a method known as differenced range versus integrated doppler (DRVID), which exploits the opposite change of group and phase velocity as the plasma density changes. The method is sensitive only to changes in the columnar electron content, not to the total content. The original purpose of DRVID (Ref. 2) was to provide charged particle calibrations for doppler data; however, it has proved useful in probing the solar plasma as well. Calibration of plasma-caused time delay in range data requires knowledge of the total electron columnar content; however, only the change in the columnar content is required to calibrate doppler data for charged particle effects. The DRVID technique is, therefore, ideally suited for doppler calibration.

Approximately 150 h of DRVID data suitable for calibration of doppler data and for studying the solar plasma were collected during the extended mission covering 4 months after the *Mariner VI* and *VII* superior conjunctions. From a preliminary study of this data, it was found that:

(1) Doppler phase-locked tracking is often valid even when the "receiver out of lock" indicator shows the data to be invalid.

(2) Solar plasma clouds with typical sizes of 6×10^4 and 2×10^6 km occur at heliocentric distances of 27 solar radii.

(3) Local electron density variations are at least a factor of four above steady-state predictions.

(4) A correspondence occurs between plasma fluctuations in the raypath and McMath sunspot regions on the solar surface.

II. Operational DRVID Description

The DRVID method is based on the apparent path differences as measured by group and phase methods in a plasma. In a dynamic plasma, the group and phase velocities are not constant but vary such that for an increasing columnar electron content the phase velocity increases by the same amount that the group velocity decreases. Range code modulation is propagated at the group velocity while doppler information propagates at the phase velocity.

By comparing the path changes indicated by range differences against those found by integrating the velocity inferred from the doppler data, a remainder results that is proportional to the number of electrons which have entered or left the raypath during the interval of observation. Note that such a technique cancels out all common effects in the doppler and range such as the earth's troposphere and more importantly the tracking station–spacecraft relative motions. Even the less prosaic effects of general relativity and possible gravity waves are removed by this differencing technique.

As shown in Ref. 2, the DRVID function is given in meter-kilogram-second units by

$$\mathrm{DRVID} = \frac{40.3}{f^2} \int_{t_1}^{t_2} \int_{\mathrm{raypath}} \frac{d}{dt}\, n(s,t)\, ds\, dt$$

where

DRVID = two-way range change, m

f = radio frequency, Hz

$n(s,t)$ = space and time variable electron density, electrons/m^3

t_1, t_2 = time limits of observation span

The columnar electron content is given by

$$I(t) = \int_{\mathrm{raypath}} n(s,t)\, ds$$

so that the change in the columnar electron content is given by

$$\Delta I(t) = 6.007 \times 10^{16}\, \mathrm{DRVID}(t), \text{ electrons/m}^2$$

for the case of S-band range and doppler tracking.

The validity of the DRVID technique, using the fast acquisition ranging system, was established in limiting cases in late 1969. In these tests with the *Mariner* spacecraft at an angular distance of 60 deg from the sun, the earth's ionosphere was measured by DRVID and independently verified by a VHF Faraday rotation method (Ref. 3). These method verification tests also established that ground equipment variations were less than 0.1 m/h.

For observations within a few degrees of the sun, independently determined solar plasma dynamics are unavailable to check the DRVID method to the required precision. Thus, an alternate, although less rigorous approach, had to be devised to test the internal consistency of the observations. The method involved eliminating the plasma contribution from the doppler data and examining the residuals for systematic effects. The internal consistency tests are valid since the solar plasma excursions are assumed uncorrelated with the inherently diurnal variations that normally occur in doppler tracking data. However, if the plasma dynamics were introduced by the earth's ionosphere, the effect would be diurnal in character and, therefore, would invalidate any doppler residual analysis to independently check the DRVID data.

III. Autocorrelation Detection Plasma Transit

The simultaneous presence of an uplink and downlink in the medium between the earth and spacecraft offers an opportunity to measure the position of plasma intersections with the radio raypath. As plasma irregularities transit the raypath, they will, in general, cause a particular signature in the DRVID data. As illustrated in Fig. 1, the plasma signature will arrive at the earth twice, first on the downlink and then again at a time τ^* when the uplink signature is received. Given a plasma stream which crosses the raypath at a particular point and persists for a time comparable to the length of the observations (several hours), an autocorrelation of the DRVID data should exhibit a correlation maximum at a time shift τ^*. Inspection of Fig. 1 shows that the domain of physically significant autocorrelation time shifts extends from zero (at the spacecraft) to a round-trip light time (at the earth).

Although independently conceived by the authors, the autocorrelation technique applied to bi-static tracking was first proposed by Thiede and Lusignan (Ref. 4), in the context of phase excursions introduced into doppler data by refractive index variations. The DRVID data type differs somewhat from the proposed uses of Ref. 4 since DRVID has sensitivity to only the charged particle effects and no dependence on relative spacecraft motion and neutral atmospheric effects.

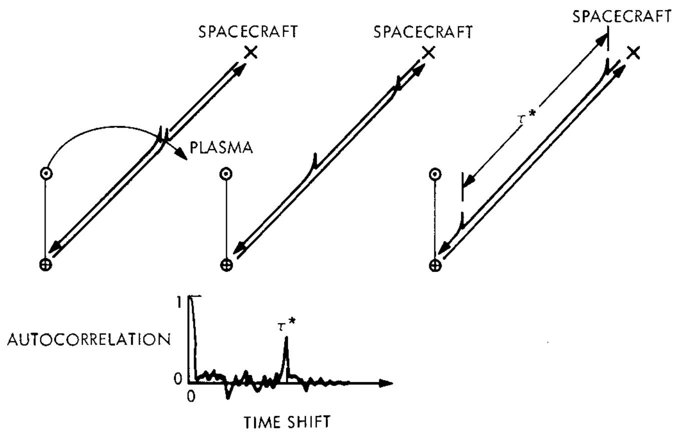

Fig. 1. Autocorrelation for location of plasma transit

IV. Observations

Figure 2 shows columnar electron changes and the range change at S-band for an event of May 29, 1970 observed in *Mariner VII* DRVID data. The spacecraft range ρ was 2.5 AU; the sun–earth–probe angle was 6 deg. The received ranging power was -190 dBm with a total uplink power of 200 kW from the 64-m tracking station at DSS 14. The curve fit to the data points is the result of a 15th-order least-squares power series. The event itself is rare because it apparently shows plasma entering and leaving the raypath. Most excursions observed were either of plasma entering or leaving but not both. The shape of

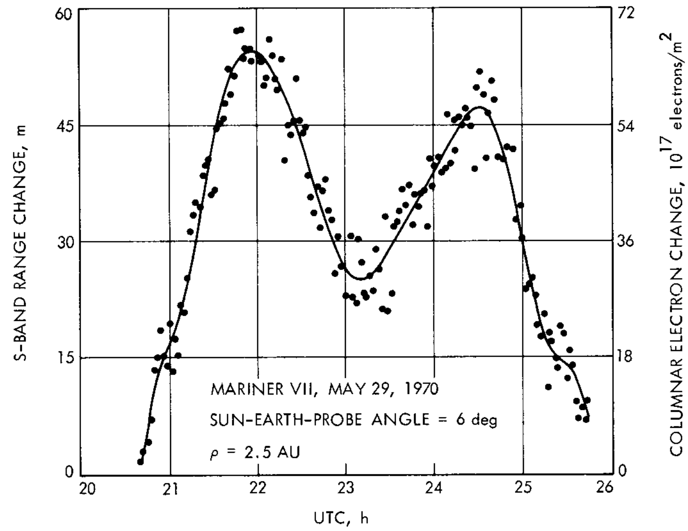

Fig. 2. DRVID-measured solar plasma dynamics

the excursion suggests the transit of two connected clouds. The change in the columnar electron content is approximately 65×10^{17} electrons/m^2. Assuming that the excursion results from two similar plasma clouds, the duration of each is about 2½ h.

Figure 3 shows the result of the internal consistency test of the DRVID data to verify that it removes the apparent plasma effects from integrated doppler orbit residuals. "Receiver-out-of-lock" indications were so frequent that these doppler data would not normally be used. The

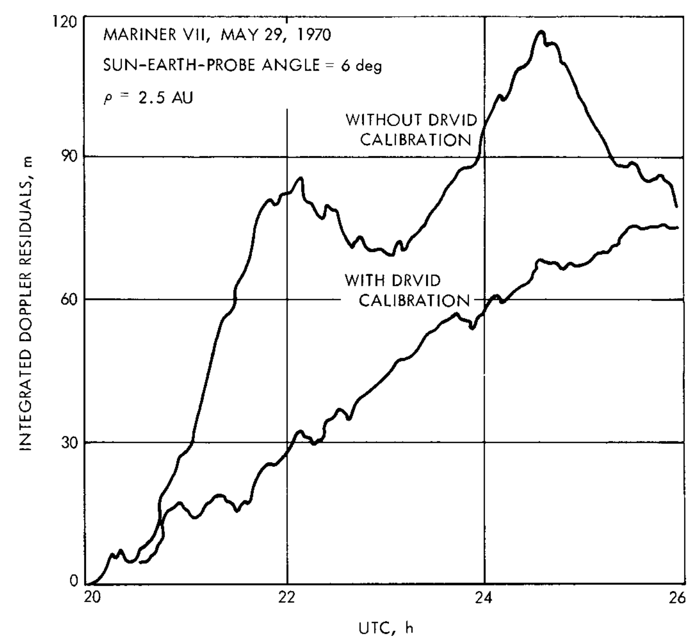

Fig. 3. Integrated doppler residuals

power series shown in Fig. 2 removes the double-humped excursion from the integrated doppler residuals. Since only a diurnal variation is left after the removal of DRVID, it is presumed that a real plasma excursion was observed and that sufficient doppler phase-lock was maintained. The diurnal signature results from using an approximate orbit to determine the doppler residuals.

Many similar events have been analyzed for data taken within a few degrees of the sun. Columnar content rates of change lasting several hours have been found up to 3×10^{15} electrons/m^2/s. It is likely that there were even larger rates of change;.however, the internal consistency test showed that there was a failure to maintain doppler phase-lock in such cases. Phase-lock failures were fortunately few, only about 5% for a month around superior conjunction. For comparison, columnar content rates in the earth's ionosphere rarely exceed 10^{14} electrons/m^2/s.

Figure 4 shows the result of autocorrelating the residuals of the individual DRVID samples from a 15th-order least-squares power series fit to the data of May 29, 1970. Relative correlation maxima occur at time shifts of 18, 24, and 36 min. The absolute significance of the autocorrelation function has been disturbed by the inability of the power series fit to adequately remove the long period (150 min) oscillation from the data.

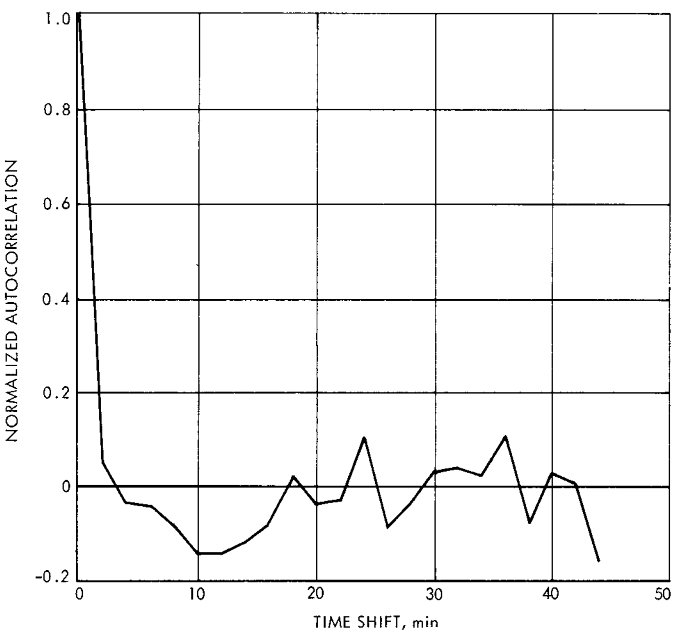

Fig. 4. Normalized autocorrelation (*Mariner VII*, May 29, 1970)

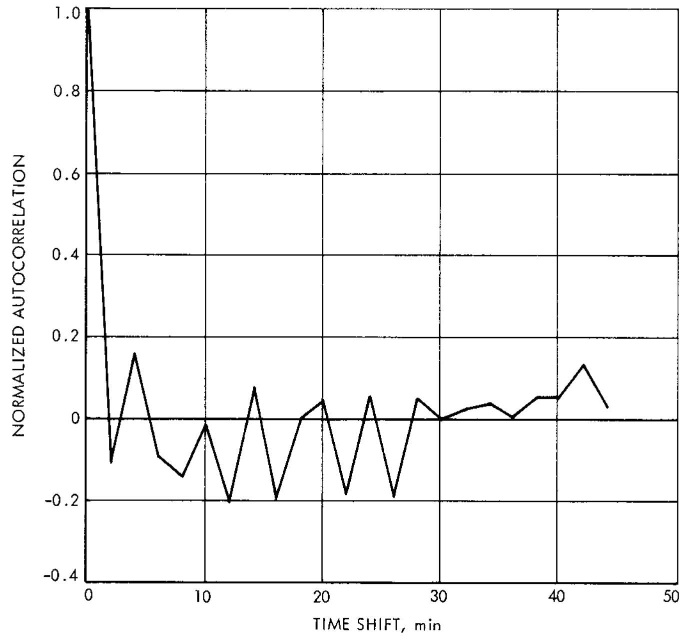

Fig. 5. Normalized autocorrelation (*Mariner VI*, June 2, 1970)

Figure 5 shows the results of autocorrelating the DRVID data from *Mariner VI* on June 2, 1970. The correlation reaches relative maxima at 4, 14, and 24 min. The round-trip light time was 43.1 min. Note the negative correlation spikes before and after each of the positive peaks. Also note the region of little fluctuation from 30 to 40 min.

V. Solar Plasma Propagation Model/Solar Surface Disturbance Correspondence

The model is quite simple: The sun rotates with an angular rate of approximately 13.4 deg/day. Ignoring heliographic latitude dependence, material ejected from the surface travels radially at a speed between 300 and 350 km/s. These assumptions result in a simple spiral structure for the streaming material. A specific example, the data in Fig. 4 for *Mariner VII* on May 29, 1970, will be helpful in illustrating the use of the model.

The correlation $\tau^* = 24$ min implies that the plasma crossed the raypath 1440 s from the spacecraft or 1158 s from the earth since the earth/spacecraft round-trip light time was 2519 s. Both *Mariner VI* and *VII* are essentially in the ecliptic plane so plane geometry is adequate. Figure 6 shows the geometry of *Mariner VII* on May 29, 1970. The radial path from the sun to the raypath plasma intersection is 0.12 AU (0.18×10^8 km). The plasma transit

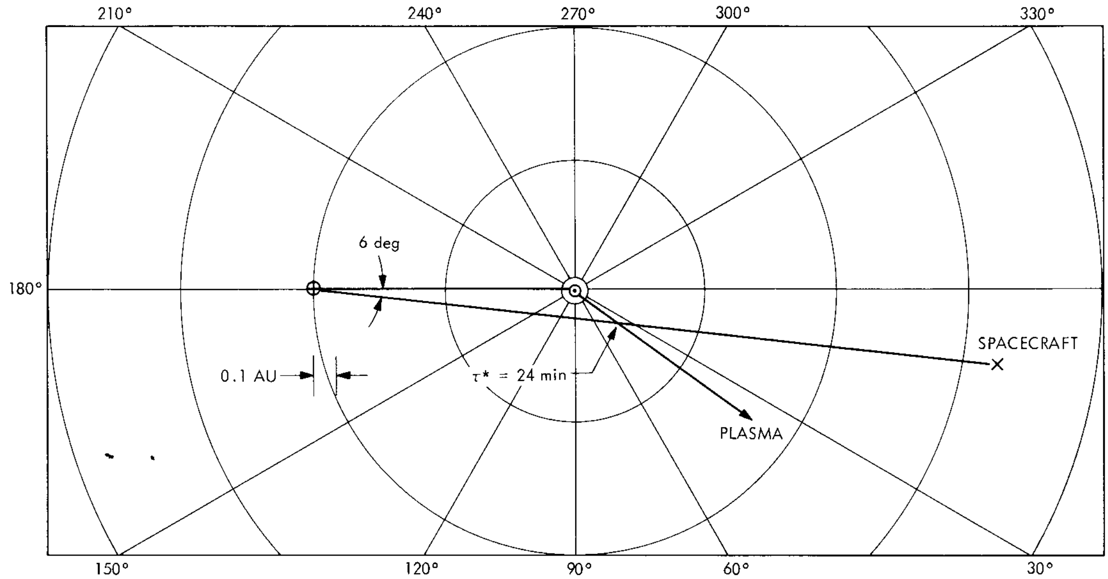

Fig. 6. Ecliptic plane geometry (*Mariner VII*, May 29, 1970)

is observed on day 149.9. Assuming an average velocity of 320 km/s, the material had to leave the solar surface on day 149.3. The assumed radial motion of the plasma requires it to have departed the sun's surface at a relative earth/sun longitude of 120°W. The question is now whether or not a solar surface disturbance is located at such a longitude at the required time. Since the relative longitude of 120°W is not visible from the earth on day 149.3, an indirect method is necessary.

The ESSA[1] Research Laboratories Solar-Geophysical Data (Prompt Reports) contain Hα spectroheliograms taken daily. In the spectroheliogram for June 11 at 23:25, UT, McMath region 789 A-B extends over a range of longitudes from 45 to 80°E. Assuming a rotation rate of 13.4 deg/day, and assuming that the 789 complex remains substantially unchanged, on May 29.3 the complex will be located between longitudes 96 and 131°W. The calculated longitude of 120°W is in the center of region 789. McMath region 789 is not observed to make a west limb transit before it is detected in the raypath. However, projecting ahead to the expected time of east limb transit for the plasma emitter, region 789 appears at the predicted time. Thus, it appears possible to observe the development of active regions on the back of the sun with the autocorrelation technique.

The other autocorrelation peaks at 18 and 36 min, by an analysis similar to that above, correspond to McMath regions 740 and 759, respectively. Figure 7 illustrates the plasma crossing and the mapping to the sun.

Three important correlations were found in Fig. 5, *Mariner VI*, June 2, 1970, at 4, 14, and 24 min, and a conspicuous lack of correlations is seen between 30 and 40 min. Using a velocity of 300–350 km/s, the 4-, 14-, and 24-min correlations are found to correspond to McMath regions 774, 781 A-B, and 792, respectively. Region 781 A-B is a return of region 743 and region 774 is a return of region 740. Note that region 740 appeared in the analysis of *Mariner VII*, May 29, 1970, 3 days prior to these *Mariner VI* observations.

Consider the lack of correlation features between 30 and 40 min in Fig. 5. Because of the peculiar mapping involving the earth–spacecraft geometry, the plasma velocity, and the solar rotation, the correspondence between correlation time shifts are found and the sun's surface is not immediately obvious. Table 1 contains the relative longitudes and dates of ejection from the sun if

Table 1. Correlation time shift τ^* mapping to longitude/time pairs on the sun's surface

Correlation time shift τ^*, min	Relative longitude, °W	Day numbers
30	32.6	152.2
32	19.9	151.6
34	12.6	151.1
36	7.9	150.5
38	4.8	149.9
40	2.5	149.3

[1]Environmental Science Services Administration.

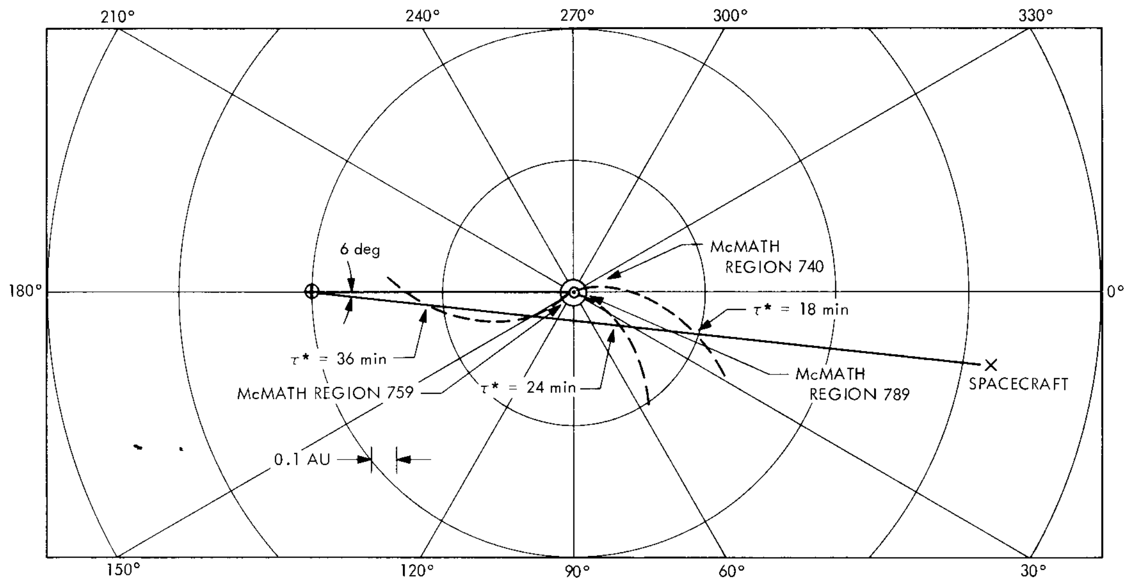

Fig. 7. Plasma transit/McMath region correspondence (*Mariner VII*, May 29, 1970)

material were to cause correlations at the specified time shifts. An examination of the ESSA data shows no active regions for the times and longitudes of Table 1. Therefore, not only do correlation maxima map to McMath sunspot regions, but regions on the sun without McMath regions produce a marked lack of autocorrelations in the DRVID data.

These examples are not isolated incidents. Many such correspondences have been made for both *Mariner* spacecraft in May and June of 1970. Over 90% of the correlation maxima found have been mapped to McMath regions in the manner described here. Several instances of long periods without correlations have been mapped to regions of no activity.

VI. Plasma Cloud Properties

For the case of *Mariner VII* on May 29, 1970, the presence of three solar surface disturbances contributing to the columnar electron dynamics complicates the interpretation; however, an order of magnitude estimate of the parameters for the clouds causing the large changes is possible. For the purposes of estimation, let us assume that the large scale dynamics of the double cloud were contributed by the region with the smallest heliocentric distance to the raypath, McMath region 789. The velocity transverse to the raypath is smaller than the average velocity of 320 km/s by the dot product of the radial plasma velocity vector and the impact vector. Thus, the transverse velocity is $v_T = 260$ km/s, implying that the clouds have a transverse dimension of approximately 2.3×10^6 km. Assuming the longitudinal dimensions of the cloud to be comparable, an estimate can be made for the change in the average electron density. The columnar content is observed to increase by 65×10^{17} electrons/m². Given a cloud of size 2×10^6 km, it follows that the average density must have changed by $\sim 3 \times 10^9$ electrons/m³ (3000 electrons/cm³). If one assumes that these plasma dynamics occurred at the position indicated by the 24-min correlation peak, then 3000-electron/cm³ variations can occur at 0.12 AU (27 solar radii).

It is of interest to compare this variation with the steady-state electron density predictions for the solar corona. Various models for the solar corona (Refs. 5, 6, and 7) all predict substantially the same electron density at 0.12 AU, approximately 700 electrons/cm³. A variation in density of 3000 electrons/cm³ is rather unexpected. There is, of course, the possibility that the plasma dynamics resulted from one of the other two McMath regions, 740 or 759. The plasma from both those regions intersect the raypath at heliocentric distances of 0.4 and 0.6 AU, respectively. The implied cloud dimensions would be 0.6×10^6 km with an average electron density variation of 10^4 electrons/cm³. Since the steady-state electron density at 0.5 AU is expected to be between 50 and 100 electron/cm³, a variation of 10^4 electron/cm³ seems hard to accept.

The DRVID autocorrelation peaks often appear to be preceded and/or followed by relative negative correlations, as can be seen in Figs. 4 and 5. These relative minima accompanying the maxima could be physically interpreted as indicating that the plasma irregularities causing the correlations are of a compression/rarefaction nature. Determining the detailed structure of the irregularities is not possible because the data frequency is limited to 2 min/sample. The indications are, however, that the correlation width of the irregularities is approximately 4 min. If the irregularities have a simple rectangular electron density compression/rarefaction structure, their autocorrelation would have a triangular shape as shown in Fig. 8. Plasma compression associated with velocity waves has been observed by Neugebauer and Snyder (Ref. 8) in data from *Mariner II*. The deviations from the triangular pattern are possibly caused by data noise and the oversimplified model. The width of the correlation triangle is proportional to the irregularity size w divided by the transverse velocity v. Using $v_T = 260$ km/s and a correlation time scale ~ 240 s, it is found that the irregularities have a typical size of 6×10^4 km. Because of the data sampling rate, the correlation time scale will always be about 240 s. If the apparent transverse velocity changes because of geometry, the correlation will be sensitive to a different size of plasma irregularity. The maximum size observable from the correlation is about 10^5 km, while the minimum is about 2×10^4 km.

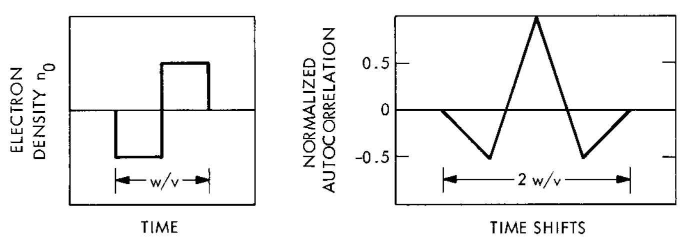

Fig. 8. Autocorrelation of rectangular plasma density variation

VII. Conclusions

The radio metric data obtained during the superior conjunctions of *Mariner VI* and *VII* have provided a previously unavailable opportunity to investigate plasma effects near the sun. The effects were found to be larger than expected. In one special case, the size of the plasma cloud was estimated to be 2×10^6 km, and a density change was calculated to be at least 3000 electrons/cm^3, more than a factor of 4 times the predicted steady-state density.

The sizes of plasma clouds observed were in the range of 6×10^4 to 2×10^6 km. The latter is a deduction being dependent only on the plasma's transverse velocity. The smaller size is inferred from the width of autocorrelations in the data. Because the correlation technique is sensitive to different cloud sizes at different points along the raypath, it appears that with sufficient data the spectrum of sizes in the range 10^4–10^6 km could be deduced.

Autocorrelating the data allows the range to plasma clouds that cross the raypath to be determined. The correlations have a structure which suggests that the electron density variations may be of a compression/rarefaction type. With a simple model of a rotating sun and radial material ejection at average velocities of 300–350 km/s, over 90% of the observed correlations can be mapped to active McMath regions on the sun's surface. McMath regions which develop on the backside of the sun are observed via the autocorrelation and their times of east limb transit are predicted to within less than ½ day. Furthermore, if the autocorrelation is observed to be particularly featureless, it is found that there are no active regions in the appropriate area of the sun's surface.

On the basis of the material discussed in this article, it would appear that DRVID can make meaningful contributions not only to doppler data calibration but also to scientific exploitation of radio metric data. From the evidence presented, there appears a probable correspondence between McMath sunspot regions and large solar wind variations. Given that McMath regions directly influence the raypath columnar electron content, it should be possible to establish weighting and selection criteria for orbit data processing based on ESSA Hα spectroheliograms, even when DRVID data is unavailable.

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