SUPPORTING STUDIES IN CLOUD IMAGE PROCESSING FOR PLANETARY FLYBYS OF THE 1970'S

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SUMMARY OF PROGRAM ACTIVITIES

Analysis of the Venus flyby data at the University of Wisconsin was begun in July 1974. V. E. Suomi and R. J. Krauss returned from residence at the Jet Propulsion Lab in Pasadena where they provided mission support and organized and prepared data for shipment to Madison. While some analysis of the images was done at JPL. The highly quantitative cloud motion measurements had to be done at SSEC. The basic tool used for analysis of the images at SSEC is the Man-computer Interactive Data Access System (McIDAS). Many of the computer programs necessary for cloud tracking and motion measurement were developed prior to July. Consequently, after a short initial period of familiarization with the image data, consistent measurements of the desired quality were obtainable during early fall.

One major new development during the summer was the implementation of a Venus limb navigation technique permitting analytic image alignment to the accuracy of a pixel. This scheme, developed by Dennis Phillips, reduces systematic error in the cloud motion measurements at 15 km ground resolution to about 5-10 meters per second for the time intervals we are investigating.

A preliminary report, covering the first few months of our Venus data analysis effort at SSEC was presented by V. E. Suomi at the Goddard Institute for Space Studies in New York on 15 October 1974. A copy of that paper is attached as Appendix A and will be published in the proceedings of the conference. A videotape display of cloud motions on Venus was also presented and received an interested response. It seems clear from our experience to date that some sort of dynamic display of the data will be necessary to convey to people a better feeling for the time domain and to supplement our presentation of quantitative facts.

FUTURE PLANS

Our immediate plans call for additional measurements on the data set reported on in the appendix. We need to improve the statistics by at least doubling the number of measurements in order to verify the structure of the velocity profiles. We have also started a detailed error analysis of the measuring process to determine the accuracy of the navigation scheme and the reason(s) for the large amount of scatter in the velocity measurements. Planning for our participation in future missions such as MJS may be impacted if we must change our data analysis procedures. If, on the other hand, the scatter is actually in the data, we must understand what it means.

Numerous causes can be proposed to account for the scatter or fine structure in our present measurements: (a) changes in cloud shape, (b) vertical wind shear, (c) local turbulence or convection, (d) small or large scale gravity waves, (e) dynamic instabilities, (f) changes in cloud thickness, (g) changes in UV absorber concentration, (h) thermal waves, (i) unexplained measurement error, or some combination of the above. The only sure way to separate these effects is to carefully search for unique identifying features. Thus, for example, convection will show up as changes in both cloud shape and albedo; gravity waves will organize into cloud motions or variations in cloud motions which have organized amplitudes, phases, and wavelengths; absorbers and scatterers will show systematic variations with viewing geometry and optical depth. What is required to make a search for these phenomena is greater statistics and a larger data base - especially making use of the high time and space resolution images.

Besides our main effort to prove out the analysis techniques, we will be continuing to experiment with McIDAS to develop new methods of communication and display, both on videotape and on film. This will remain a secondary goal, however, until we have completed verification of the Mariner Venus data analysis procedures.

APPENDIX A

"CLOUD MOTIONS ON VENUS"

by

Verner E. Suomi

A Paper Presented at the Venus Symposium,
Goddard Institute for Space Studies
on 15 October 1974

CLOUD MOTIONS ON VENUS

Verner Suomi, University of Wisconsin

I don't purport to offer a general review, but I think we will find some of the results which have followed from the movie you have just seen to be fairly interesting.

As you know, the images from the Mariner 10 camera are a part of a team effort; several of the team members are here today. When I talk about the results, you must appreciate that all of the individuals participated in the planning and execution, and of course in some of the arguing about the results of the experiment. The detailed measurements on the pictures were done by my colleagues from the University of Wisconsin, Mr. Bob Krauss and Mr. Sanjay Limaye. They did most of the work and deserve the credit.

I would like to talk very briefly about what clouds can tell us. Displacements of cloud markings or cloud texture can indicate winds. If one has sufficiently accurate navigation, that is if one can relate items in the object plane to positions on the planet, one can obtain velocities. In the instances in which one does not have good enough navigation to indicate the exact angles, one can still obtain an indication of wind shears.

Now there are, of course, difficulties with using clouds as atmospheric tracers. I want to emphasize these difficulties and take a few minutes to illustrate how carefully we treat them. How we handle these problems may affect how much of our conclusions you will be willing to accept at the end.

First, we must consider the cloud scale. On the earth, for example, a large-scale cloud system several thousand kilometers across might indicate the motion of the storm and not the winds. On the other hand, a very small cloud is difficult to resolve, and usually the small clouds have a shorter lifetime than the large clouds.

Moreover, we need inactive clouds, ones which merely drift with the wind, rather than those which are changing dynamically. For example, suppose a cloud on earth were a large rapidly expanding cirrus envelope; as the cirrus cloud expanded a component due to the expansion would be added to the general motion. These effects can be seen on a video tape recording of the navigated Venus images. The TV image is too small for all of you to see in this room, but it will be set up in the hallway this afternoon so you can see for yourselves. In some of the pictures you will clearly see that the clouds are growing. Thus it can make a great deal of difference if one makes the measurement on the forward edge of the cloud or on the following edge of the cloud. On the other hand if one uses the center of mass of the cloud as the marker, he may get somewhat different results.

Another difficulty arises from the unstable imaging geometry. Those who have use ground-based telescopes have both a stable platform and stable film. The geometry in the image is preserved very well indeed. On the spacecraft, on the other hand, we have a "rubbery" film. It is called a vidicon. This does not preserve image geometry very well, furthermore, it is not a very accurate photometer. The photometry must be corrected to remove image shading. In the movie which was presented, these effects were hidden. Fictitious velocity effects are easy to see in movies made from greatly enhanced photographs. One finds that the position of the terminator fluctuates. The terminator must be fixed in space on the time scale of the movie, so that error must be removed also. Despite these several difficulties, it is possible to obtain fairly good results, if one is very careful.

I have tried to indicate some of the problems that must be overcome when one attempts to use TV images quantitatively. We will give you more details later. One must not ignore the real advantage over ground based observations, i.e., higher resolution, shorter time intervals, perfect seeing. But we will be making greater demands on the observations. We will want to observe the global distribution of the planetary motions, but before we do, we want to point out that there is other valuable information in the images.

Except for atmospheric motions, images are not useful indicators of atmospheric state parameters such as temperature, pressure, or composition. Images are, however, surprisingly good indicators of processes underway in the atmosphere. For example, the images reveal convective activity which implies certain vertical motions. It is also possible to see wave motions. There are good examples of these processes in the earth view shown in Figure 1 which was taken from Mariner 10 on its way to Venus.

In the upper left part of Figure 1 one can see waves in the cloud field which could be fairly small-scale waves or billow clouds. In the lower middle of the picture, one can see polygonal-shaped cells. This is very typical of shallow convection, i.e., that which occurs when the atmosphere is heated from below or strongly cooled from the top, but with a definite lid on convection under a strong inversion. In another part of the image, there is a cloud cluster which indicates deep vertical motion.

Images can reveal processes, at least qualitatively. Convection and wave motion are typical examples, but one might go so far as to say that there may even be indication of the global heat budget. Areas where the energy received by the planet is greater than the energy lost by the planet tend to have convective clouds, whereas areas for which the loss from the planet exceeds the gain from the sun tend to have more stratified clouds. This seems to be true on the earth, too. Images can be a useful qualitative indicator of processes but we have not reached the stage where one can be quantitative about it.

Clouds can be indicators of the general circulation also. The most obvious examples are the circulation zones. This is certainly true for the earth, and may be true on Venus and other planets as well. We have jet streams which are fairly easy to identify, and large-scale storm features which we have already mentioned.

Images of the planetary cloud field behavior can also show long-time instabilities. The Venus flyby shown in the movie is a very limited 8-day sample of the Venus circulation. On the other hand, the large number of ground-based observations show that other motions or changes in the circulation pattern could be present.

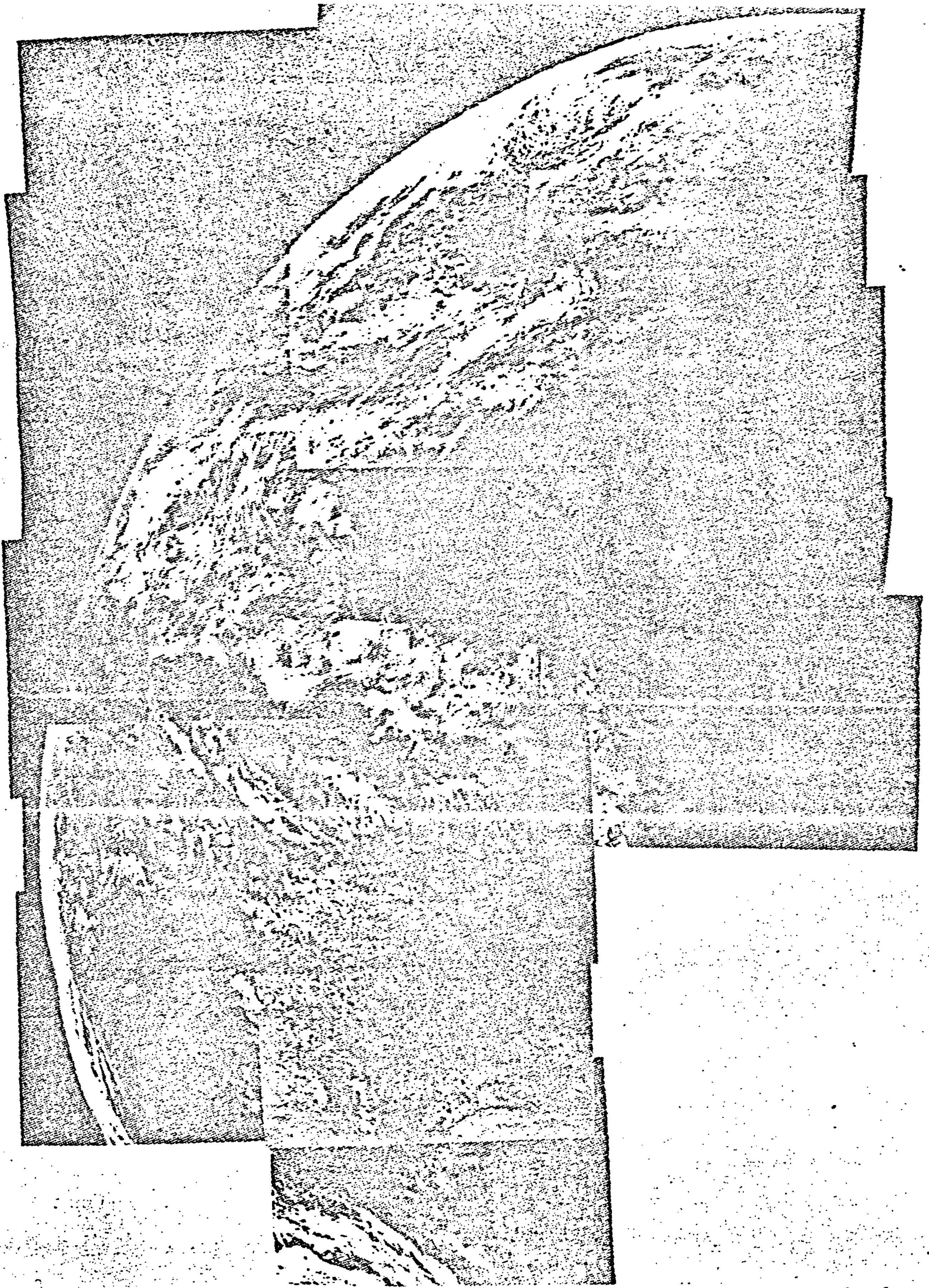


Figure 1 Mosaic of Mariner 10 images of earth. Most of the cloud features in the lower half of the mosaic are over the pacific ocean. In the upper half, the clouds over the Gulf of Mexico and the United States are seen. Polygonal cells can be seen in the lower middle of the mosaic and wave associated clouds can be seen in the upper left of the picture.

I do not propose to review the ground-based observations to an audience containing individuals who have been busy taking these beautiful observations for many years. They are far more familiar with them than I could ever hope to be. What I can say, however, is that the close-up views given by the Mariner 10 flyby have made these observations even more valuable, because we can now better interpret what can be seen in the ground-based observations. I emphasize again that the Venus flyby observations encompass only 8 days, enough for only two trips of the clouds around the planet. There are decades of ground-based observations. Lifetimes of the large-scale features can be studied using ground-based observations. They cannot be studied as well from Mariner 10.

The ground-based observations record the features of the whole planet at the same time or for the same time interval. The close-up pictures of Venus shown in the early frames of the movie are a mosaic of many pictures which span a good fraction of an hour. There is a distortion in the UV markings because all parts of the image were not photographed simultaneously. We will say more about this latter.

Figure 2 of Venus is illustrative of things which I mentioned already. It is a Mariner 10 photo of the subsolar area, which there is evidence of convection. This photo, taken early in the flight, has fairly high resolution and has hexagonal cells in several places. Polygonal cells are clearly evident many places in the picture and it is evident that convection is occurring.

Figure 3 is a photograph taken at a high latitude where streamers torn from the main cloud indicate a stratiform cloud with strong horizontal shear. This photo was also taken when the spacecraft was quite close to the planet.

DR. SAGAN: Vern, could you point out one or two polygons?

DR. SUOMI: It is possible, depending on the degree of convection, to have polygons where the walls are cloudy and the space in between clear. Here [in Figure 2] is such a polygon.

DR. INGERSOLL: You are making the assumption that dark spaces are clear and light spaces are cloudy?

DR. SUOMI: Yes, I am making that assumption. Obviously, if I wanted to show a picture of Venus as you and I would see it, I should just take out the slide and show you a bright blank screen! In the ultraviolet, however, there is much contrast and Figure 2 is what you see in an enhanced photo. On the earth we have two kinds of cellular cloud systems, those where the walls of the hexagon are clear and the space in between cloudy and others where the walls are cloudy and the space within the hexagon clear. Generally speaking, when the convection is strong one tends to have the cloudy walls. For our purposes, i.e., to illustrate a convective process on Venus, it makes little difference if we assume black clouds— cumulous bituminous -- or white clouds in a dark aerosol background. The effect is the same. It's only a matter of degree. But, as the lawyers say, a change in degree is a change in kind.

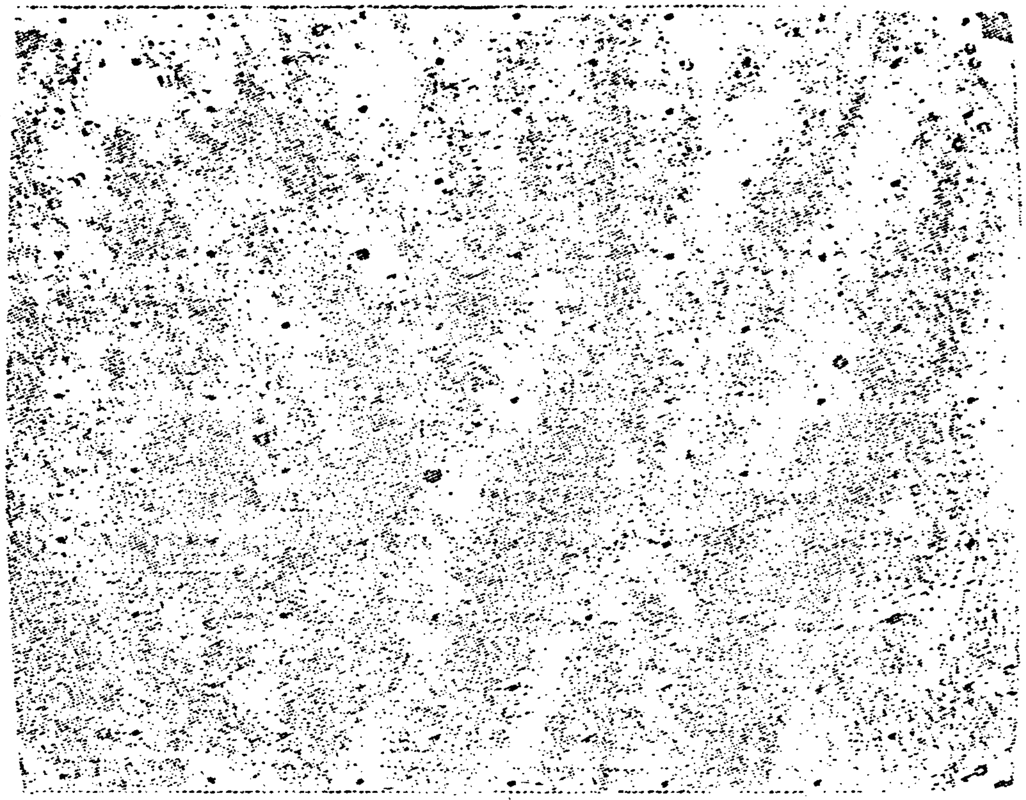


Figure 2 Mariner 10 photograph of Venus showing the sub-solar region. The image has been stretched to show contrast. Some cellular structure can be seen in this and other images of the sub-solar region.

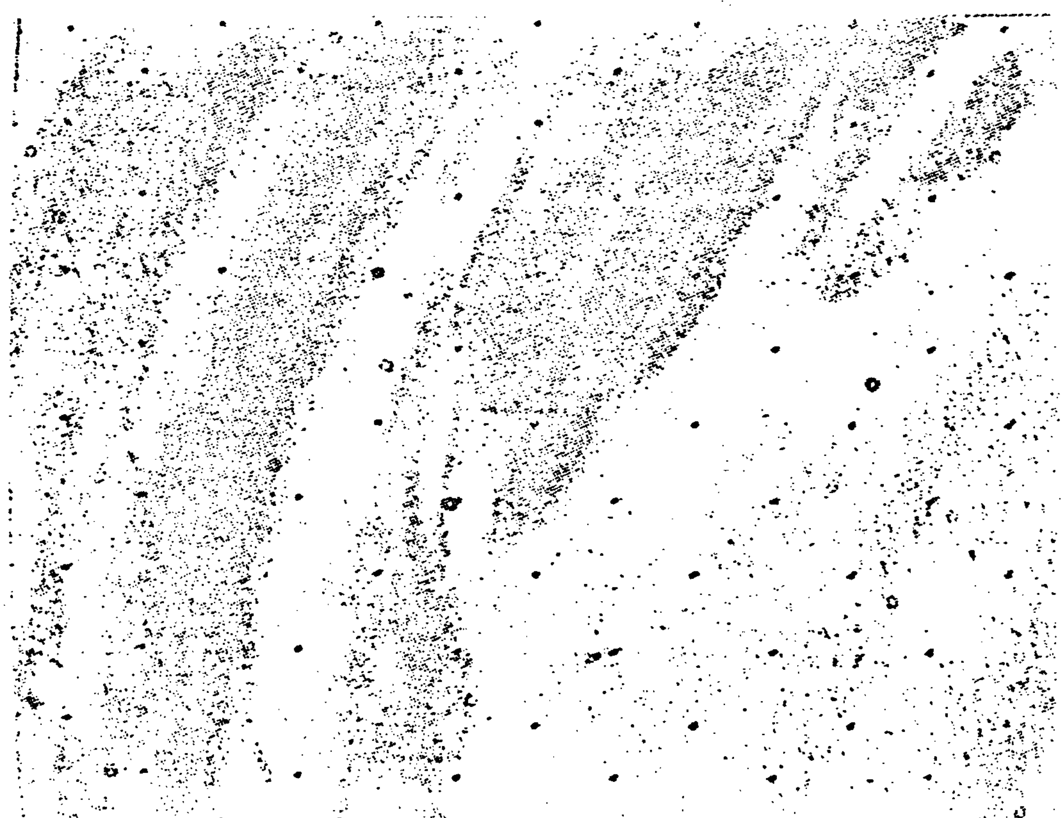


Figure 3 Mariner 10 view of high latitude region of Venus (southern hemisphere). The large bright region in the lower right has its periphery along about 50 degrees latitude circle. The streamers along this edge may be caused by large velocity shears.

There are very many Venus photos which show evidence of convection, and many more which give evidence for horizontal wind shear. Now whether or not the convection we see is evidence for the presence of condensates is a different story. In this case the time scale is very important. If clouds or markings have a long liftime there could be dust-like material forming the markings, but if the time scale of formation and decay is short then it is more likely that the markings are a result of some condensation processes.

Figure 4 shows examples of markings which look like convective clouds. The contrast has been greatly stretched and it is a much clearer example than you saw in the movie. The same figure shows examples of convective cells which are preserved in two pictures taken about 2 hours apart. These patterns are very characteristic of the cloud structure one sees in satellite pictures of clouds in a sub-tropical high on earth.

My point of showing you evidence of convection is not to dwell on the Venusian convective processes in themselves, but to indicate that the motions of the markings are likely to represent motion of the atmosphere also. Furthermore, the changes in the markings over time scales of an hour or so do, as I have already mentioned, affect the accuracy of our measurements. If a marking were to remain fixed in shape over a time period of hours, one could get quite accurate results. However, if the cloud is changing shape rapidly one is not certain he is tracking the same target. On the other hand, a cloud does not change shape very much in time intervals of minutes, but it doesn't move very far in that short time interval, so the percentage accuracy of the distance measurement is poorer over short time intervals. As you will see later, an automated computer analysis requires that there be little shape change, but it can measure displacements very well. On the other hand an operator can track a cloud even it it undergoes considerable changes in shape, but he cannot measure the distances as well.

Ed Danielson already mentioned that it was necessary to correct for vidicon shading. Figure 5 is an example of a photo of a uniform field, but with a maximum contrast stretch -- to show that the response is far from uniform. What appears to be a signature of Channel 7 television is actually caused by a reflection from the cathode in the vidicon tube. Blemishes appear everywhere on the faceplate. Actually these represent only small signals, but they are visible here because of the very high contrast stretch. The photos in the movie and those used in our analysis appear to be uniform, but you must appreciate that they have had extensive shading corrections and considerable contrast stretch. Moreover, because each target in a sequence of pictures is normally photographed on a different part of the vidicon target area these corrections can actually contribute to further errors in cloud displacement observations.

The movie was made from a large number of pictures. The measurements we have made came from a very small number of these pictures. In order for you to understand just what was done, I am going to describe the important procedural details listed in Table 1.

Figure 4a UV markings in the sub-solar region which look like convective clouds. Such features are fairly long lived. Figure 5 shows one feature which can still be seen two hours later (arrow shows the position).

Figure 4b A photograph of the same general area, taken about two hours after the one shown in Figure 4.

I M A G E P R E P A R A T I O N

At Jet Propulsion Lab

FICOR - Vidicon Shading Correction

GEOM - Automatic Reseau Finder

- Remap to Object Space

- Scale Factor Proportional to Distance from Venus

Prepared Data Tapes Sent to
University of Wisconsin

Table 1. Preliminary image processing needed before images may be used for feature tracking

FICOR, a Jet Propulsion Lab analysis program removes vidicon shading. That's number one. Secondly, GEOM uses the Reseau marks and remaps the scene in object space rather than image space. Remember that image space not only contains minor optical distortions, but also contains larger distortions which are due to non-linear raster scanning and charge distribution distortions. In addition GEOM takes into account the changing scale factor due to the change of distance to Venus. The output of GEOM is a new magnetic tape. We wish to acknowledge JPL's effort to provide us with these processed tapes.

The next step in the analysis is to superpose one image matrix on another so the planet's reference frame is fixed. We call this process image navigation. This is fairly easy to do for a sequence of images of the earth because landmarks can be used as reference points. It is much more difficult on Venus since we do not have any reference points. Worse yet, the limit cycle in the Mariner 10 spacecraft stabilization system and the need to move the camera scan platform caused very large changes (measured in terms of the camera field of view) in pointing angle. If one looks at a series of raw pictures it is as though one were looking at a planet through a telescope hanging on a string in a high wind! The picture sequence moves very erratically.

The errors in pitch and yaw sometimes amounted to half the image or more -- and sometimes were even greater since Venus didn't even show up on the picture. Fortunately the roll error was much less, only about a quarter of a degree, since the roll control was tied to Canopus and was very stable. Large yaw and pitch errors are easily removed by displacing an image left or right and up or down. There was no need to rotate the image. Under these circumstances it is possible to use the planet's limb as a reference. The navigation scheme used the best fit to a sphere for 5 points on a bright limb. Other inputs were lines per frame, elements per line, the height of the frame in degrees, the width of the frame in degrees, and the distance to the Venus surface. The navigation program was developed at the University of Wisconsin by Dennis Phillips.

Figure 6 shows the navigation geometry used in the program. Both the sub-spacecraft point and the subsolar point are known precisely. A line passing through these points can be represented as a single scan line in the TV image. From this information a conventional grid of latitude and longitude can be obtained.

Table 2 shows the various error sources. The geometric rectification in the FICOR program was accurate to about 1 pixel out of the 700 lines and 832 pixels in a horizontal line. The navigation model fit was accurate to 1 pixel. The latitude and longitude grid definition is good to about 1 pixel because it is the result of a best fit. Round-off and truncation errors account for half a pixel. The total error, then, could add up to 2 pixels.

Single-point tracking, a technique in which a cursor is manually tracked on the moving TV image, could add about 1 pixel due to granularity plus several pixels due to the operator. The same operator may get a pixel or two variation each time he tries to track a specific object.

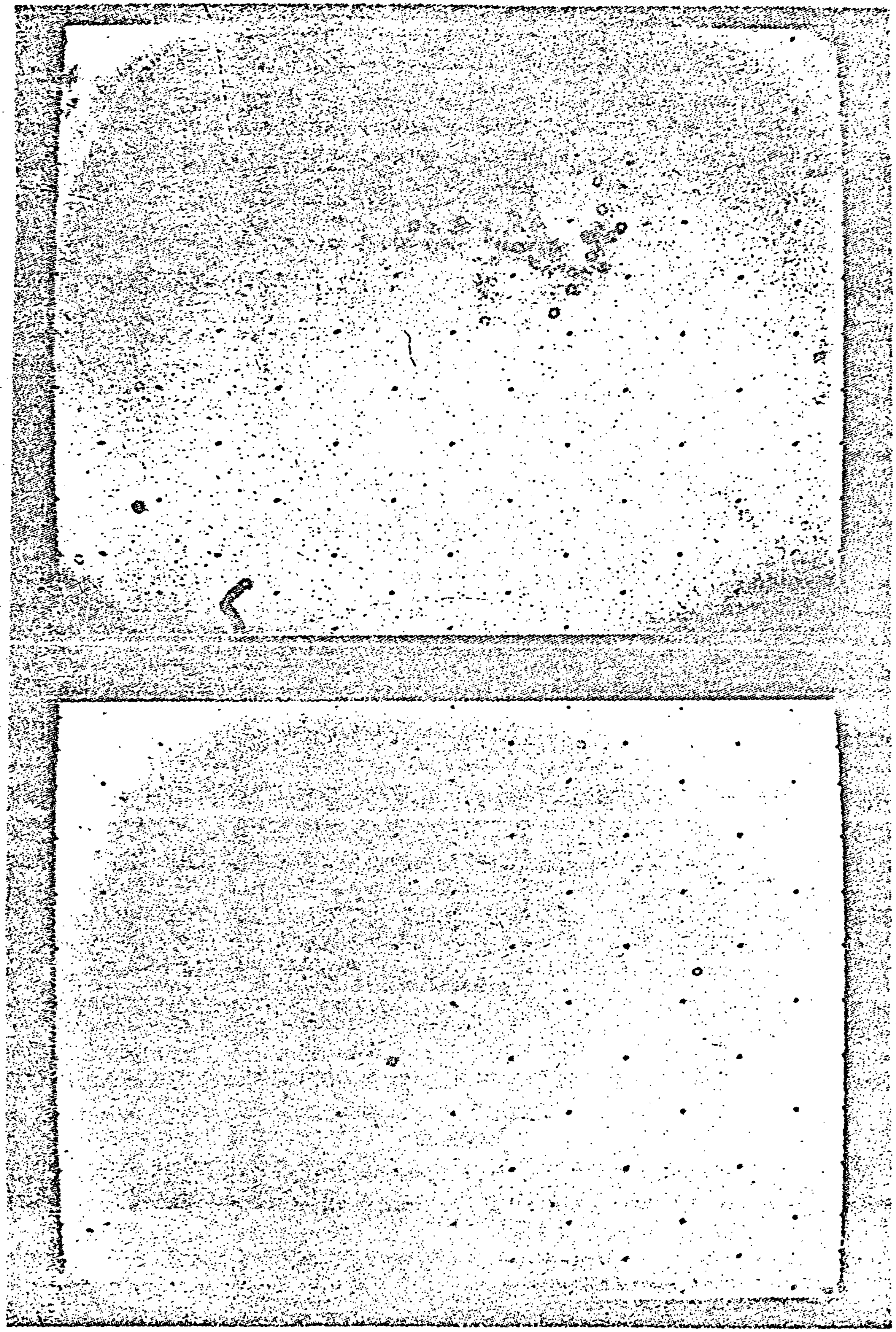


Figure 5 Contrast enhanced flat field vidicon image, Camera A top and Camera B, bottom.

ERROR SOURCES

GEOMETRIC RECTIFICATION	~ 1 pixel
NAVIGATION MODEL FIT	~ 1 pixel
LAT - LON GRID DEFINITION	~ 1 pixel
ROUNDOFF & TRUNCATION	~ 1/2 pixel
RMS ERROR	~ 2 pixel

SP Tracking Adds 1 Pixel Granularity in Measuring Plus Up To Several Pixels For Operator Accuracy

RMS ~ 4 - 5 pixels

Table 2. Various sources of error in the measurements of motion of the UV markings. In addition to these the spacecraft roll error also contributes somewhat to the final results. This component has been ignored as a first approximation.

Table 3 shows how pixel errors and time intervals affect velocity errors. It is clear that one can exchange time interval length for greater accuracy even though the pixel error is large. On the other had if the time interval is too long the cloud changes shape. A compromise must be made between trying to take as short an interval as possible in order that cloud shape is preserved, and a long enough interval to minimize distance error.

We used four techniques to track the clouds. One of the ways is single point tracking. In this technique the operator controls a cursor superimposed by the computer on the image; thus there is no parallax error. The accuracy is mainly limited by the skill of the operator.

In the other three schemes, the operator merely chooses an area in the first picture to be tracked and a corresponding larger area in the second picture which includes the same cloud or marking. The remaining processes are completely objective: one image matrix is correlated with a second image matrix in the computer. The techniques are summarized in Table 4. The peak in the correlation surface is a measure of the displacement. I apologize for going into such great detail on the techniques of analysis but it may be helpful in assessing the results of our analysis. Please understand that we have just begun our image analysis following these procedures and the results I now show you are what we obtained from the first few pictures.

Table 5 shows that 47 targets were measured repeatedly, with four norms applied over six different time intervals. The correlation failures occur when the correlation peak is at the image matrix edge due to effects of different cloud patterns in the second scene. These correlation failures were rejected. The measurements over T_2-T_3 were also rejected. This interval was very short and one needs very high resolution to be able to use very short time intervals. In order to trust a measurement over a series of time intervals, one had to obtain more-or-less the same velocity in several intervals. We rejected those which did not repeat within 15 m/s or 2σ for a given cloud target. With these rejections 620 measurements of the over 1000 on the 47 targets remain.

Figure 7 shows velocities as a function of latitude using the completely objective computer technique only. A solid curve which represents a velocity profile for which angular momentum is conserved has been superimposed. The dotted line represents a velocity profile of constant angular velocity. Note that the curve is slightly different for each figure but the functional relationship is essentially the same. Figure 8 is similar but the velocities were obtained by single pixel tracking, which gives slightly larger error bars (RMS deviations after 15 m/s edit) but less scatter since the computer operator is less sensitive to changes in cloud shape.

Although the data is noisy, there is evidence that the winds in mid-latitude regions of the planet are blowing slightly faster than they are in equatorial regions.

What we have is the following possible structure. In the polar zone, there is an indication of solid rotation or constant vorticity but outside this region, on the equatorword side of the polar ring cloud, there is conservation of angular momentum. Such a velocity profile would require some meridional motion - we have measured a small amount.

TABLE 3

VELOCITY ERROR

(15 km/pixel Resolution)

PIXELS SHIFTED	km SHIFT	VELOCITY INCREMENT FOR A GIVEN TIME INTERVAL (m/s)				
		15 MIN.	30 MIN.	1 HR.	1-1/2 HR	3 HR.
1	15 km	16 m/s	8	4	3	1.5
2	30	32	16	8	6	3
4	60	67	33	16	10	5
6	90	100	50	25	18	9

Table 4

CORRELATION TECHNIQUES

NORM	PREDOMINANT SENSITIVITY
EN - Euclidiean Norm	Detail in Image
CC - Cross Correlation	Edges & Details
LP5 - Fifth Power Norm	Light & Dark Patches
SP - Single Point Tracking	Operator Opinion

EN, CC, LP5, Use Quadratic Interpolation to search for maximum in correlation matrix- good to <0.1 pixel.

SP uses line & element selected by operator - good to 1 pixel.

Table 5

M A R I N E R 10 V E N U S A N A L Y S I S

A T U N I V. O F W I S C.

47 Targets Measured Repeatedly

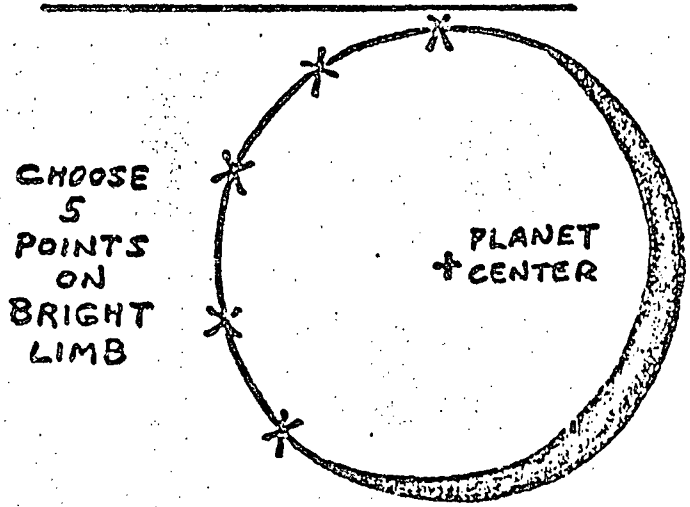
with 4 Norms over 6 Different

Time Intervals

TOTAL MEASUREMENTS	1194
CORRELATION FAILURES	187
SUCCESSFUL CORRELATIONS	1007
SUCCESSES WITHOUT T2-T3	887
>15 m/s DEVIANTS FROM TARGET MEANS	267
GOOD VECTORS REMAINING	620

IMAGE NAVIGATION

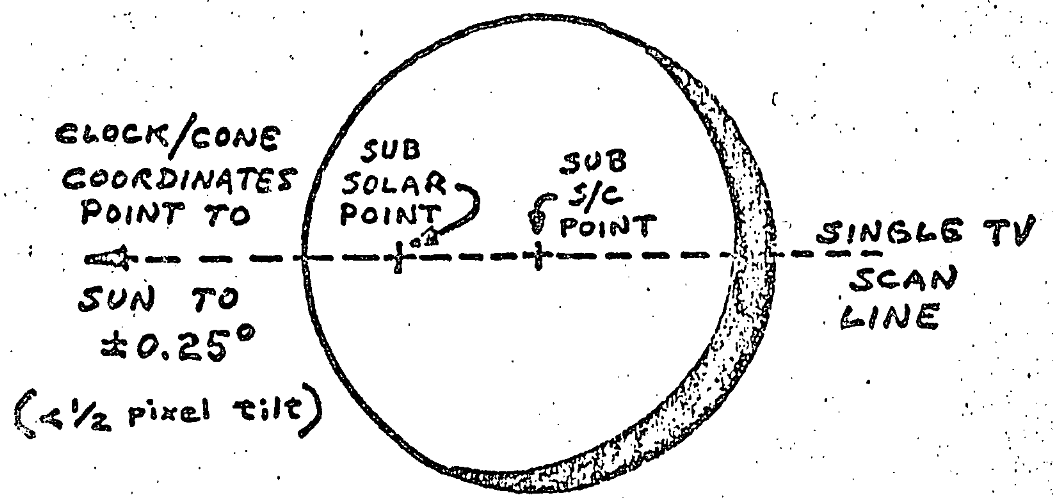
BEST FIT TO SPHERE:



INPUTS

- LINES PER FRAME
- ELEMENTS PER FRAME
- HEIGHT OF FRAME (deg)
- WIDTH OF FRAME (deg)
- DISTANCE TO VENUS SURFACE

LAT-LON GRID DEFINITION:



- LATITUDE OF S/C SUB POINT
- LONGITUDE OF S/C SUB POINT
- LATITUDE OF SUB SOLAR POINT
- LONGITUDE OF SUB SOLAR POINT

Figure 6 The basic inputs to image navigation. The contribution due to roll error is ignored in the first approximation.

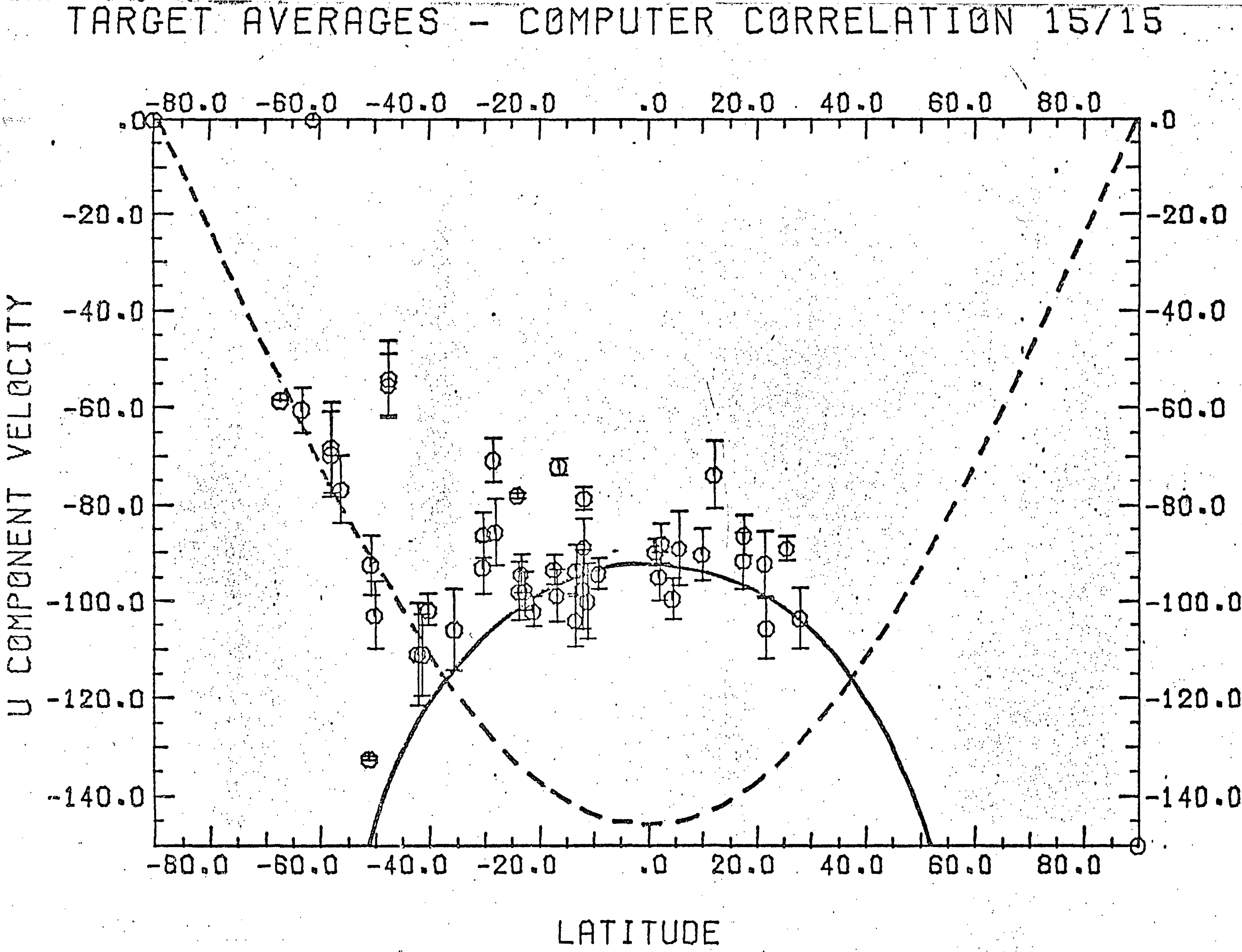


Figure 7 Meridional Profile of the zonal component of cloud motions measured by computer correlation techniques.

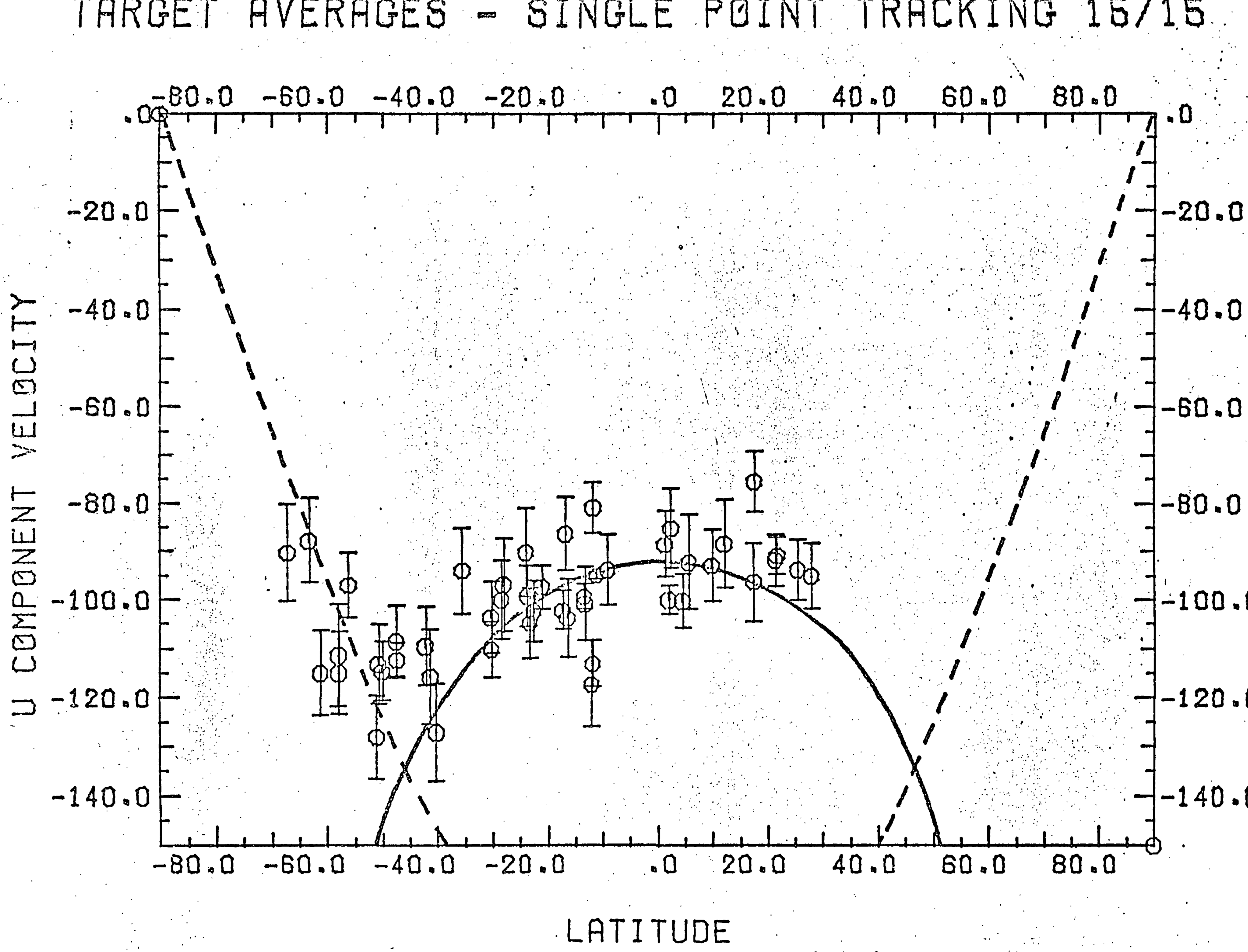


Figure 8 Meridional Profile of the zonal component of cloud motions measured by single pixel tracking. The computer operator

Leovy has shown that the North-South horizontal pressure gradient which exists on Venus could be balanced by the horizontal component of the centrifugal force. Using this scheme and the velocity profiles we have just shown, it is possible to derive a North-South "pressure" profile also. Clearly, a low must exist over the pole with pressure rising toward the equator to form a high pressure belt over the equator. But because of solar heating a bulge must exist on the belt.

This is one man's picture of what the circulation looks like, but clearly credit should should be given to Hadley who thought it up in the first place. The Venus circulation looks like modified Hadley circulation.

Figure 9 shows a vortex generated using a spinning cage. The diagram is from a thesis by Nicholson who has developed a model of a vortex which contains friction. This vortex is only a few centimeters in diameter, but he finds the same structure for much larger vortices including hurricanes. In the outer regime one has conservation of angular momentum. There is solid rotation in the central portion. His model requires a mass sink.

Meridional motions on Venus also require a mass sink in the polar region. Also if there is conservation of angular momentum and a mass flow as suggested, prograde motions are required elsewhere on the planet so that the total angular momentum is conserved.

Figure 10 is further evidence for the velocity profile just suggested. It is a photograph due to Dr. Mike Belton, who used a central meridian section of a number of Venus photos and assembled them as a mosaic.

It is interesting to use the velocities which we obtained and ask: How far would a cloud in the polar belt move zonally compared to one in the equatorial region. If one uses our values and of course takes into account that we have a crude Mercator projection, one finds that the polar cloud should move about twice as far, much as it appears to have moved in the mosaic. Moreover, there is a curvature in these bands. The shapes of these bands could be an indication of the lifetime of the particular cloud entity. If a cloud had a very long lifetime it would pass around the planet many times, and would be stretched virtually into constant latitude lines. On the other hand, if the residence time is very short, one would not get these spiral streaks at all. I am proposing that the shapes of the UV markings are indications of North-South velocity shear and meridional motion.

It seems to me, using some imagination to be sure, that it would be possible to use these features in some of the ground-based pictures as an indication of the cloud velocity profile. The angle of streakiness, it seems to me, might be used as an indicator of the meridional shear, and possibly even as an indication of the meridional motion.

Well, these are the main points I wanted to make. I would guess from now on the debate will be very lively.

DR. POLLACK: What evidence have you that the motion you see of individual spots is really a motion of air rather than wave motion?

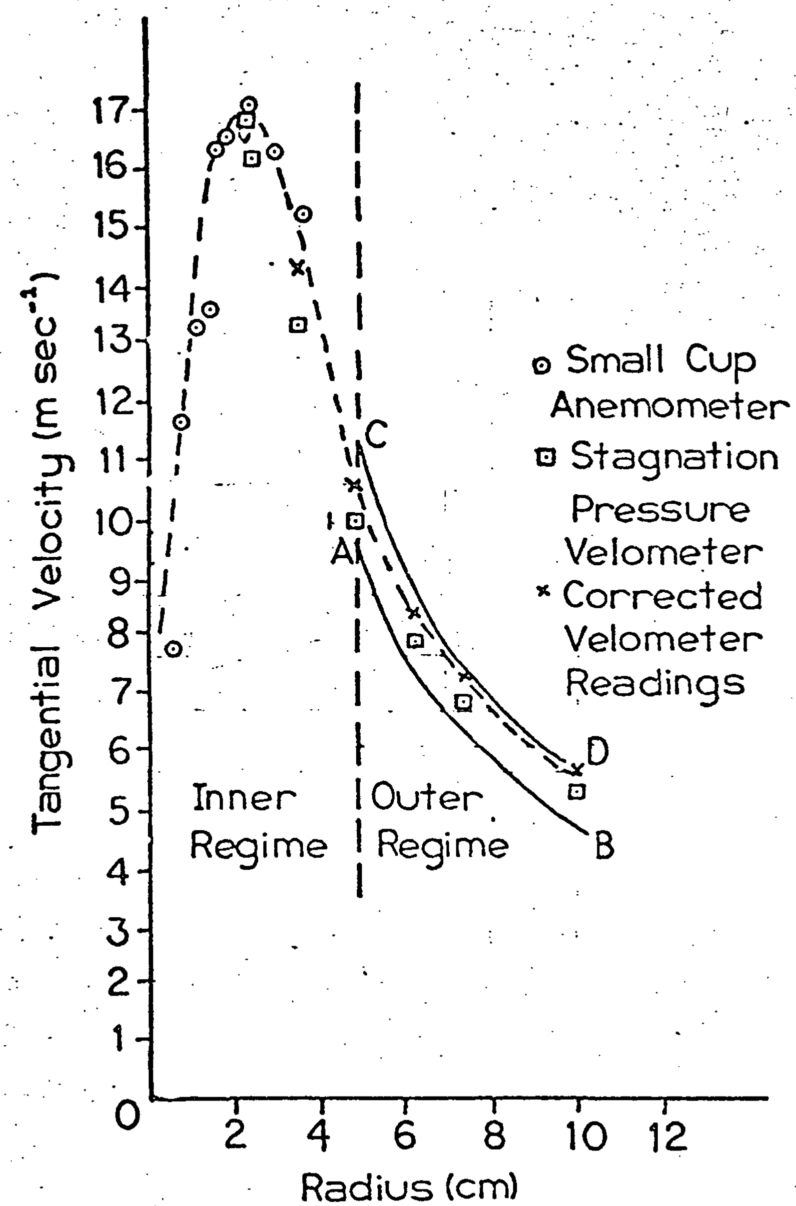


Figure 9 A vortex model depicting the tangential velocity as a function of radial distance from the center of the vortex. (After F. Nicholson, Ph.D. Thesis, Univ. of Wisconsin, 1971).

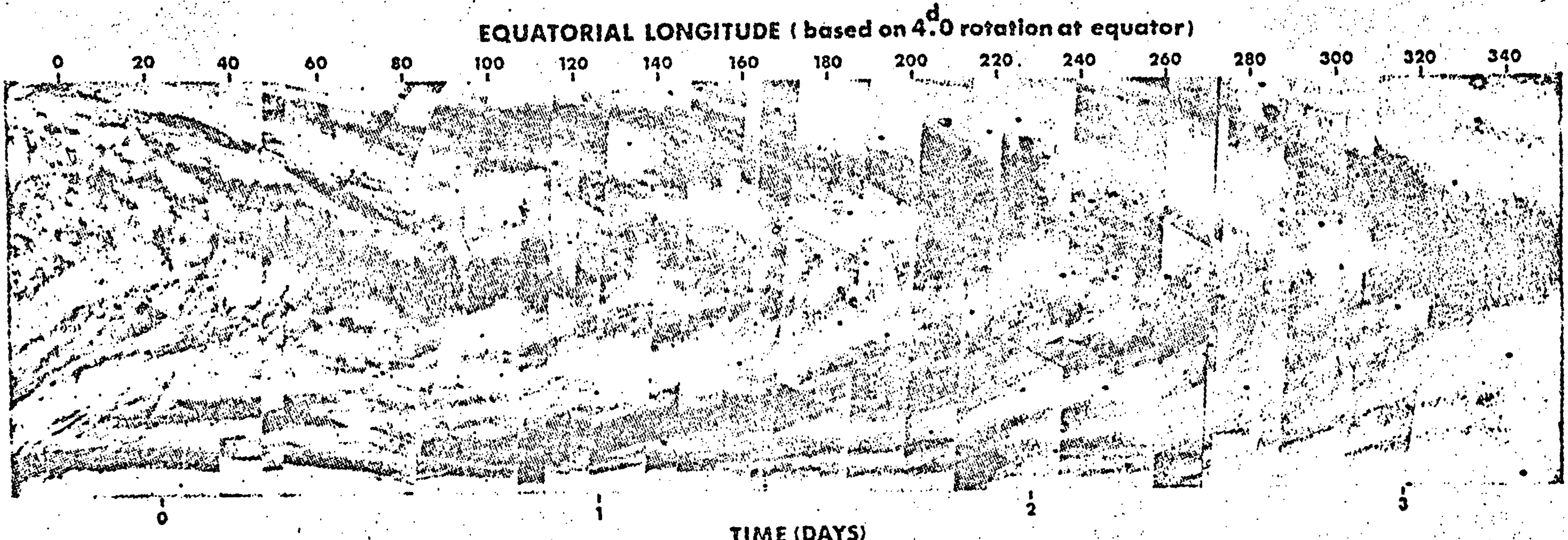


Figure 10 A mosaic of central portions of the Venus disk from Mariner 10 images made over a 4 day period, forming a pseudo-mercator projection.

DR. SUOMI: Many years ago when I first proposed using clouds for obtaining wind motions on the earth, there was very little acceptance of the idea. In fact, when I first proposed it, I thought I would be shot at sunrise.

I can only say that the preponderance of evidence on earth is that the clouds form a very good indicator of the air motion, providing one is careful. It is possible to see gravity waves. It is possible to measure the motion, the phase velocity of those waves. In that regard you are absolutely right. However even with orographic clouds, "fixed" to mountains, it is possible to measure the motion of the cloud texture.

I cannot guarantee that these are indeed the actual air motions. I would think, though, that as one got to higher and higher resolution, we could see smaller clouds. The smaller the cloud the better the marker. With large clouds, the dynamical effects might predominate. The motion of a large cloud system could represent the motion of the storm rather than the winds in the storm. So the motions of the markings might not be the air motions. But from my experience looking at many clouds, and here of trying to be as objective as possible, including results "untouched by human hand," so to speak, they seem to be moving as shown. I would have to fight with the data to change the profile you saw.

DR. ANDY YOUNG: I am a little disturbed by the fact that in your selection of correlation, and so on, you wind up throwing out something like a third of your data. I wonder if your results aren't partly a result of some selection effect, in which you've thrown out the data the don't agree with what you subconsciously expect to find and you've kept the ones that look right to you.

DR. SUOMI: Well, we tried not to do that. There is something wrong when one gets a 2 sigma error on the same cloud for several time intervals. We thought of using all the data. It would be noisier, but the profile would still look the same.

DR. RICHARD YOUNG: For what latitude were you quoting the meridional velocity? Did you see structure with latitude?

DR. SUOMI: We did not see any structure with latitude for the meridional velocities. I think you would have to say that we didn't see strong meridional velocities, but we clearly saw at least a couple of meters per second. I think that most of our measurements are on the equatorward side of the bright cloud, and that our meridional velocities may have been reduced by the so-called cigar effect problem. My guess is that the meridional velocities may be slightly higher. What we should have done was balance out the meridional velocity errors attributed to one side of that cigar cloud with some of the other side. So far this exercise has taught us how to go at it, and these are the preliminary results.

[Post-conference note: Figure 11 illustrates the meridional component of the SP cloud motions as a function of latitude, shown why a-2 $\pm$ 5 m/s average was obtained. Least squares fits indicate a slope of about 1 m/s per 10 degrees latitude with zero velocity near the equator. Scatter is greatest in equatorial regions, indicating that convection, local turbulence or vertical shear are probably present.]

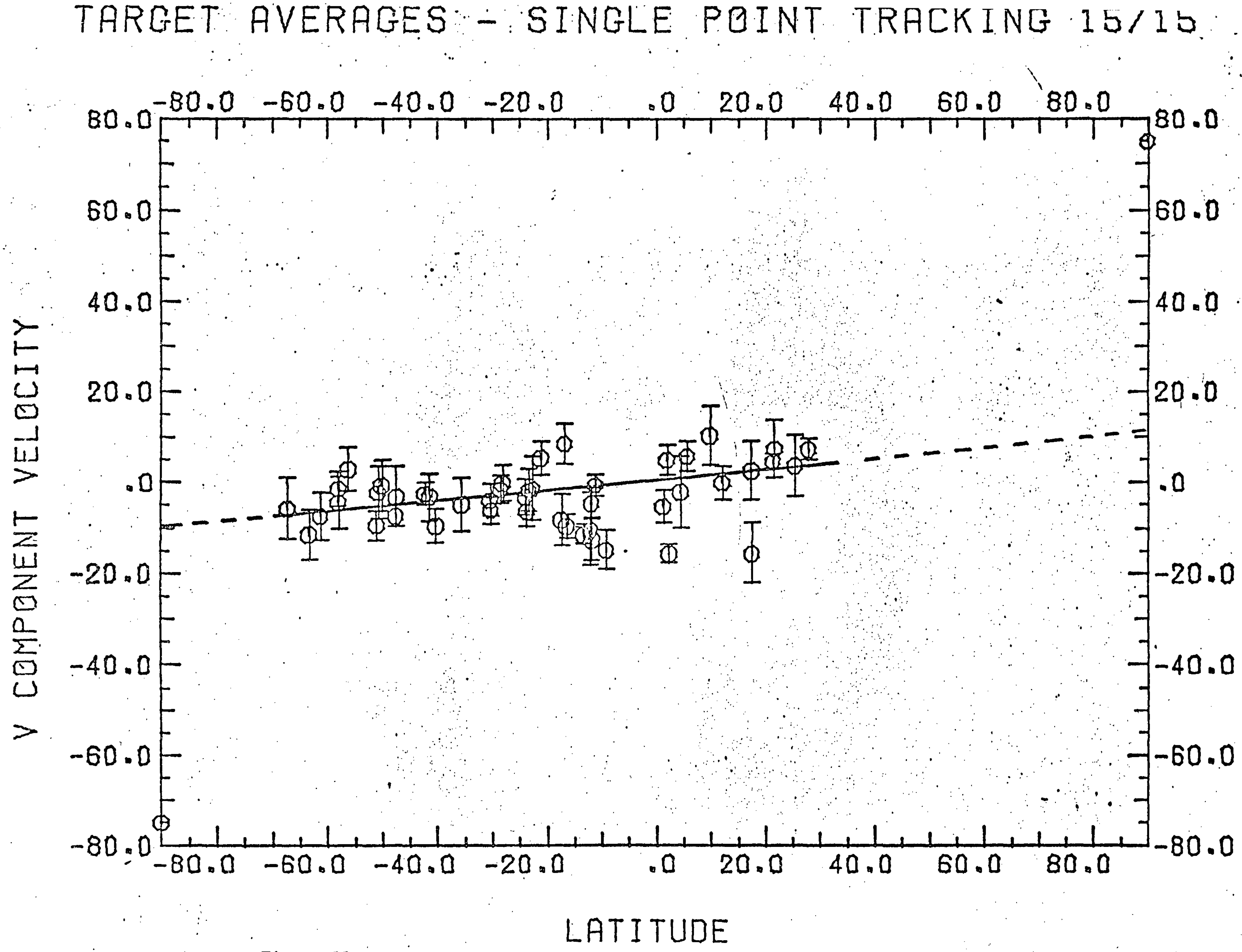


Figure 11 A profile of meridional motion component as a function of latitude, measured by single pixel tracking.

DR. RICHARD YOUNG: The 5 m/s meridional velocity was at what latitude?

DR. SUOMI: That was not 5 m/s. That was the variance. The -2 m/s was the average for all latitudes.

DR. JONES: What was the smallest scale feature you could see in all of these photographs and how did that compare to your theoretical resolution?

DR. SUOMI: Of course, it depends on what we are using. If we are using the correlation schemes, then we are dealing with patterns. When we were dealing with single pixel tracking, we tried to do it by looking at some feature. We made a judgment about where the brightest spot was, where the edge was.

DR. JONES: There are two things that are seemingly in contradiction. Up until today, in looking at these pictures, I had always assumed that these patterns appear to show a flow spiraling toward the pole. You see these wide things and you see individual cloud lines, all of which are in the form of a helix going up toward the pole.

The other thing, of course, is that these patterns seem to rotate in a rather fixed pattern, going about the planet as a fixed pattern. This latter fact is consistent with the fact that you find that there is practically zero poleward velocity, -2 m/s, with an uncertainty of 5 m/s.

So I wonder if you have an explanation for how these patterns could simply rotate in a fixed configuration.

DR. SUOMI: Well a streamline and a trajectory are not necessarily the same. Let us assume we had a barber pole. In fact, we had a herring-bone barber pole. I would see the strip move from the middle toward the top and bottom of the barber pole.

DR. JONES: How do you paint the barber pole?

DR. SUOMI: That is up to the painter.

Now imagine a fly on the barber pole, and the fly to be at rest. He will obviously describe a circle, and will appear to describe a horizontal line as you view him at the same height. On the other hand, if the fly decides to walk up, you get a different slanted line. And I think these are the things we ought to consider.

I think the clouds are marks, and the marks get distorted by shear. If I could have an ideal cloud, from the pole to the equator, than I claim that cloud would bend because of the meridional shear, and it would not move very much at the pole. In the zone from the equator to 40° it would move faster. So the cloud line would bend to an extent depending on its residence time. If it stayed, not moving out of a latitude, it would eventually generate a fixed straight line. Since Figure 11 shows tilted streaks, the clouds which compose them must move meridionally.

DR. STONE: I found it very interesting that the explanations that have been proposed in the past for the zonal circulation have emphasized the Halley-type circulation, diurnal circulation. You emphasize the Hadley-type circulation which does not explain the zonal motion per se. My own feeling, for reasons that I will give tomorrow, is that you've got to have some of both.

DR. SUOMI: I wouldn't be surprised.

DR. STONE: But nevertheless, it is distressing that you don't find any meridional circulation.

DR. SUOMI: I'm sorry, it is incorrect to say there is "no" evidence of meridional motion. We got -2 m/s. True, it is buried in a large variance, but that's what we got. I think when one asks how one can get a motion which is going faster at high latitudes where there is less solar energy, one requires some mechanism, and the conservation of absolute angular momentum is such a mechanism. For any mechanism which provides the greatest amount of motion where there is the greatest amount of heat, the highest velocities should be on the equator. But the highest velocities are not on the equator.

DR. SHUBERT: I got the impression from your plots of velocity versus latitude that the preponderance of evidence was that the velocity was constant with latitude, and there were very few observational points at the highest latitudes with a faster velocity.

DR. SUOMI: Let's look at the figures again [Figures 7 and 8] which show the velocities obtained from the computer. You, of course, have to be aware that it is easier to measure near the equator than near the pole. We have few low velocities in the polar region, and more high velocities at mid-latitudes. You could argue that the navigation is in error and gives us a spurious result. That is possible. But the reason I went into all that detail describing our procedure was to show you that we tried our damndest to not have that error. I want to say again that most of the actual measurement work was done by Bob Krauss and Sanjay Limaye. They are the ones who put the hours in to try to resolve these things.