SYNERGY BETWEEN ENTRY PROBES AND ORBITERS

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ABSTRACT

We identify two catagories of probe-orbiter interactions which benefit the science return from a particular mission. The first category is termed "Mission Design Aspects". This category is meant to describe those aspects of the mission design involving the orbiter that affect the science return from the probe(s). The second category of probe-orbiter interaction is termed "Orbiter-Probe Science Interactions", and is meant to include interactions between oribter and probe(s) that directly involve science measurements made from each platform. Two mission related aspects of probe-orbiter interactions are delivery of a probe(s) to the entry site(s) by an orbiter, and communication between each probe and the orbiter. We consider four general probe-orbiter science interactions that greatly enhance, or in certain cases are essential for, the mission science return. The four topics are, global context of the probe entry site(s), ground truth for remote sensing observations of an orbiter, atmospheric composition measurements, and wind measurements.

1. INTRODUCTION

The principal distinguishing measurement feature of atmospheric entry probes/surface landers, as compared to observations from orbit or flyby spacecraft, is that probes/landers typically make in-situ measurements. Conducting remote sensing of a planetary atmosphere or surface in order to obtain composition, cloud information, thermal characteristics, or winds, usually involves the inversion of spectra obtained with various forms of spectrometers or radiometers yielding results that are model dependent. Particular key measurements can be identified that cannot adequately be made remotely, either because the sensitivity of measurement is insufficient to measure the desired quantity to the required accuracy, or because there is no feasible remote sensing observation that can return the desired information.

On the other hand it is often desired to know the global distribution of key quantities, and this is only feasible from an orbiter. Entry probes/surface landers give essentially point measurements at the entry location, either by providing vertical profiles of atmospheric quantities at one horizontal location, or a measurment from a particular surface location. The optimal program is a balanced set of in-situ and remote sensing observations that complement each other.

We identify two catagories of probe-orbiter interactions which benefit the science return from a particular mission. The first category is termed "Mission Design Aspects". This category is meant to describe those aspects of the mission design involving the orbiter that affect the science return from the probe(s). The second category of probe-orbiter interaction is termed "Orbiter-Probe Science Interactions", and is meant to include interactions between oribter and probe(s) that directly involve science measurements made from each platform. Examples from each category are discussed below.

2. MISSION DESIGN ASPECTS

Two mission related aspects of probe-orbiter interactions are delivery of a probe(s) to the entry site(s) by an orbiter, and communication between each probe and the orbiter. Delivery of probes from an orbiter has the potential to allow access to desirable probe entry sites that otherwise could not be reached. Communication between probe(s) and orbiter has the potential to allow access to desirable probe entry sites that would not be available by direct communication to Earth, as well as the potential of direct science collaboration. Examples using past missions to Venus and Jupiter will be discussed below to illustrate how such probe-orbiter interactions can pay off in the future.

Fig. 1 (adapted from [1]) shows the distribution of the Pioneer Venus probes in a coordinate system fixed with respect to the subsolar point on Venus. Also shown is the distribution of the Venera series of probes. The four Pioneer Venus probes and the Venera probes up through Venera 8 were delivered by a dedicated bus spacecraft and communicated directly to Earth. The PV small probes were released almost simultaneously from the probe bus, with the large probe having been released a few days earlier from the same bus. Note that because of the communication constraint directly to Earth, all these probes entered either on the night side of Venus or in the early morning, local time. On the other hand, Veneras 9-12 all communicated either with a flyby parent spacecraft (V11-V12) or an orbiter (V9-V10). These probes were able to descend in the noon and afternoon regions of the atmosphere.

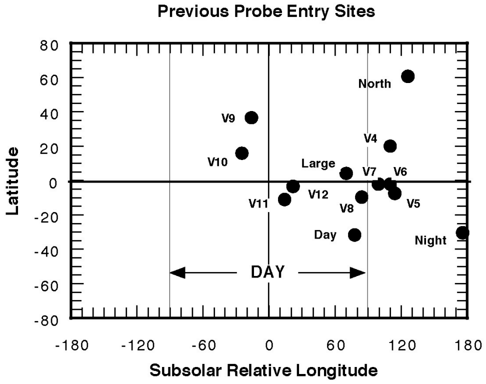

Fig. 1. Locations of previous probe entry sites at Venus, in subsolar longitude. Adapted from [1]. Subsolar point is at center of figure. The probes designated Large, North, Day, and Night are the PV probes. The other probes are Veneras 8-12.

There are meteorological reasons why reaching local noon and later meridians is desirable. For example, there is evidence of convective cells having large horizontal scales (500-1000 km) occurring at cloud levels in the mid to late afternoon local time ([2] and references therein). This could be evidence that the thermal structure of the atmosphere differs significantly in the afternoon from what has been measured in the early morning and night regions. If so, there are implications for understanding the Venus superrotation and related circulation patterns, as well as mixing of trace species from the surface to cloud levels, which in turn affects cloud microphysics and composition. But, as Fig. 1 illustrates, accessing afternoon regions of the atmosphere depends on communicating with an orbiter (or possibly flyby spacecraft) and not directly to Earth.

Of even higher current science priority is reaching particular regions of the Venus surface. It has been established by the science community [3] that it is imperative to determine the elemental and mineralogical composition of the Venus surface at a variety of sites, including especially the highland tessera. Such information is essential in trying to understand how Solar System terrestrial planet formation may have been similar or different among the planets, and in what ways differences may have occurred.

Fig. 2 is a topography map (originally in color) produced by the Pioneer Venus Orbiter [4]. The tessera are located in the high regions, but the lowland plains are also of interest. Each type of region should be sampled, and preferably at multiple sites. In order to so will almost surely require both delivery by, and communication with, an overflying spacecraft for each landed science package. It would be highly unlikely that all desired landed sites would be accessible by probe/landers launched from a single carrier on a flyby trajectory, nor is it likely that probes at such diverse sites would each be able to communicate directly to Earth. Therefore, an orbiter component to a Venus mission investigating the surface and/or atmosphere would seem an essential part of the mission.

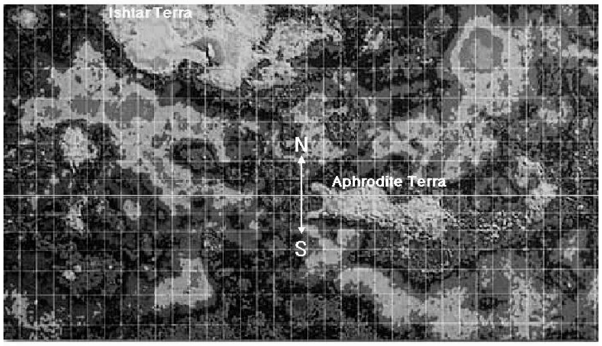

Fig. 2. Venus topography as determined from the Pioneer Venus Orbiter. Figure adapted from [4]. In translation to black and white from original color figure, most relative altitude information is lost. Certain regions, for example, Ishtar Terra or Aphrodite Terra, contain very high topography. However, the figure illustrates the diversity of terrain on Venus.

Turning now to Jupiter, the Galileo Mission illustrates the need for probe-orbiter interactions in a number of ways. Here we will consider only probe delivery and communications, but later, various other science aspects also will be discussed.

The Galileo probe was released from the orbiter about 5 months and 80 million kilometers from Jupiter. There were a number of mission trajectory constraints [5], but the mission was designed such that the orbiter overflew the probe entry site near the Jovian equator during the probe descent through the atmosphere. This allowed the probe telemetry to be received by the orbiter in real time. In future Jupiter probe missions there are strong scientific reasons for targeting probes to mid and high latitudes [3]. There are a number of technical challenges associated with entry of probes in regions other than the Jovian equator, and probe delivery and communication will be a central mission design issue.

The optimum communication strategy for a probe entering Jupiter's atmosphere, in terms of probe telemetry data rate, is communication with an overflying spacecraft. The reasons are as follows.

First, such a scenario minimizes the communciation path length. Since probe telemetry signal amplitude is inversely proportional to distance squared from the probe for a given antenna radiation pattern, minimizing the path length minimizes the attenuation of the probe signal, and hence maximizes the amount of science data that can be returned.

Second, because of thermal protection and trajectory considerations, probe mission arrival scenarios will likely dictate that probes enter in the late afternoon or early evening, local Jovian time. For example, the Galileo probe entered Jupiter's atmosphere near the equator but at a solar zenith angle of 67°. Therefore, the probe's initial descent was very near the evening terminator on Jupiter, such that by the time the probe reached the 15 bar pressure level (about 45 minutes into the mission), Jupiter's rotation caused it to be descending on the night side of the planet.

Communication losses through the atmosphere due to absorbers and clouds are minimized if the comminication path is vertical or nearly so, as would be the case to an overflying spacecraft. For probes entering in the late afternoon, or at mid to high Jovian latitudes, communication to Earth would have a long slant path through the atmosphere, causing more probe telemetry attenuation. In addition, probe communication would be rather limited in time before no signal could be received at Earth due to Jupiter's rotation, combined with rotation of the receiving station on Earth due to Earth's rotation. For these reasons it seems likely that optimal probe missions to the outer planets will involve associated orbiters, or at least flyby spacecraft.

Beside the probe entry site accessiblity issue, there may be direct scientific gain to be had because of a probe-orbiter telemetry link. For example, one of the very significant, but unanticipated, scientific benefits of the Galileo probe-orbiter telemetry link was derivation of the vertical distribution of the abundance of NH_3 by inversion of the probe-orbiter radio signal amplitude as a funtion of depth [6]. This turned out to be one of the most important results from the probe mission, first, because the abundance of N in the form NH_3 is central to understanding the evolution of Jupiter; second, there was no other method that was capable of deriving the vertical distribution of NH_3; and finally, the observed NH_3 abundance profile behaved in a totally unanticipated manner below the upper NH_3 ice cloud deck (NH_3 vapor condenses directly to ice to form the upper cloud layer on Jupiter). Prior to the Galileo probe mission, the Jovian C/N ratio was thought to be about 2 times solar, but the probe results showed that $C/N \approx$ solar. This result necessitated a major change in thinking about how Jupiter acquired its inventory of heavy elements (see [7] and references therein for discussion of all these aspects of the NH_3 abundance).

In summary, there are at least three mission design aspects involving orbiters that have significant potential for enhancing science return from a probe mission: a) delivery of probes to desirable entry sites, b) communication between probe(s) and orbiter, thereby enabling access to desirable probe entry sites, and c) science measurements that directly take advantage of a probe-orbiter telemetry link. The previous discussion of the Pioneer Venus and Galileo missions has illustrated examples in each of these areas.

3. ORBITER-PROBE SCIENCE INTERACTIONS

We identify four general probe-orbiter science interactions that greatly enhance, or in certain cases are essential for, the mission science return. Each will be illustrated below for Venus and Jupiter as was done before, but each is applicable to any probe mission. The four topics are, global context of the probe entry site(s), ground truth for remote sensing observations of an orbiter, atmospheric composition measurements, and wind measurements. More topics can probably be considered, but we limit the discussion here to these four.

3.1 Global context

The importance of obtaining the global context of entry probe site(s), usually from an orbiter, can be illustrated by the experience of the Galileo probe mission. Planned high resolution approach images of the Galileo probe entry site, to be taken by the Galileo orbiter just before probe entry, were canceled in the mission sequence because of the failure of the Galileo orbiter high gain antenna and the occurrence of other orbiter spacecraft complications. This had the potential of leaving unknown the particular cloud and atmospheric features through which the probe descended, thereby leaving the global context of the probe measurements uncertain.

As it turned out and as described below, ground based measurements were able to identify the atmospheric feature into which the probe entered, and this identification has been crucial for trying to understand and interpret various aspects of the probe data. However, ground based observations cannot always be counted on to provide the appropriate contextual information, and therefore, such information obtained from an orbiter (or possibly flyby spacecraft) is almost essential .

Fig. 3, taken from Fig. 3 in [9], illustrates the probe entry and descent trajectory, projected on NASA IRTF 4.78 μm false color images of the probe entry site. Several points are apparent from the figure. First, the probe apparently descended in the southern region of a 5 μm hot spot. These are regions located slightly north of the Jovian equator that correspond to local clearings in the clouds. They are bright near the 5 μm region of the spectrum because thermal emission from deeper atmospheric levels near 4-5 bars is being observed. The southern location of the probe entry site in the hot spot is significant for interpreting the probe wind observations (cf. [8]).

Second, the probe was within the hot spot (at least as far as horizontal position) throughout the entire descent portion of the mission, descent portion meaning that part of the mission where the probe was making direct atmospheric measurements. Immersion in the hot spot was an important factor for understanding the vertical profiles of condensible species. In fact, had we not known that the probe descended in a hot spot, interpretation of the composition measurements would have been extremely difficult, if not impossible (cf. [7] and references therein for detailed discussion).

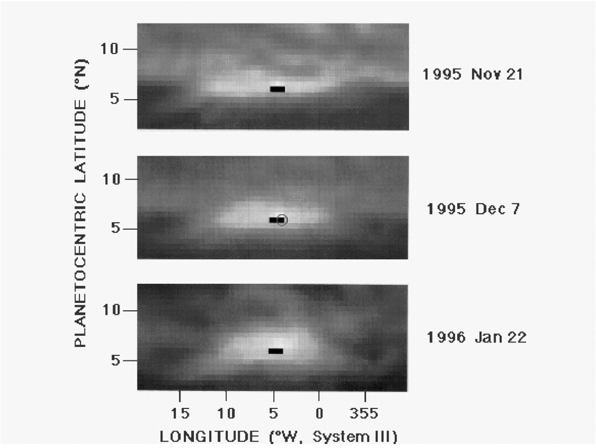

Fig. 3. Location of the Galileo probe entry site within the entry hot spot, taken from [9]. Images were taken by the facility near-infrared camera at the NASA IRTF at the summit of Mauna Kea in Hawaii. The dark bar depicts the longitudinal extent of the probe entry path starting from 450 km above the 1 bar pressure level. A 1-σ circle shows the effects of pointing uncertainty of the telescope on the location of the final portion of the probe entry. The panels from different dates were aligned together using a drift rate of 103 ms^{-1} relative to System III.

Third, the hot spot maintained its integrity for the two month period illustrated in the figure, and actually did so for much longer [9]. This is a crucial property of hot spots that must be matched by theoretical models attempting to simulate conditions at the probe entry site.

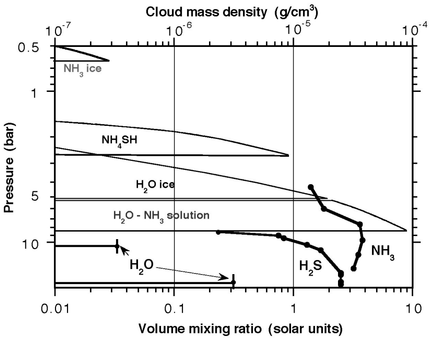

Fig. 4. Condensible species abundance profiles measured by the Galileo probe, together with a thermochemical equilibrium cloud model (see [7] for details).

Fig. 4 illustrates the vertical profiles of the condensible species NH_3, H_2S, and H_2O as observed by the Galileo probe [10]. Prior to the probe mission it was expected that the abundances of the above species would correlate with their cloud condensation levels. So that, for example, NH_3 abundance would have a constant mixing ratio below the NH_3 ice clouds, and follow close to a saturation mixing ratio for some distance above the cloud bottom. Fig. 4 shows that that is not at all what was observed for NH_3, nor for any of the other condensible species with regard to their respective cloud condensation levels (note H_2S combines with NH_3 to form the NH_4SH cloud). Furthermore, each species increased with depth below its condensation level at a different fractional rate than the others. Although NH_3 and H_2S were observed to eventually reach constant mixing ratios at depth, H_2O did not at any depth sampled by the probe.

Based on knowledge that the Galileo probe descended in a 5 μm hot spot, models of hot spots have been proposed that can at least qualitatively, if not completely quantitatively, explain the observed vertical abundance profiles of the three condensible species (e.g., [8]). It is now believed that the unusual vertical distributions of NH_3, H_2S, and H_2O are the result of the peculiar atmospheric dynamics associated with the hot spot through which the probe descended.

Had we not known the global context of the Galileo probe entry site, the above situation would have been almost impossible to comprehend, and the science return from the probe mission would have been significantly degraded. Similar conclusions can be reached for probe missions to Venus in which understanding the dynamic meteorology or spatial variations in composition are important goals. An orbiter giving the global context of probe entry sites is extremely valuable, especially since we will either not always be able to obtain such information from Earth, or not be able to obtain it from Earth with sufficient spatial resolution to be useful.

3.2 Ground truth

As was mentioned previously, a great strength of having both probes and an orbiter in a planetary mission is that both local *in-situ* and global remote sensing science measurements can be accomplished. Orbiter measurements have the capability to extend probe measurements over global scales, place the probe measurements in global context, and remotely sense regions not accessible by probes. On the other hand, probe measurements can be a great aid to orbiter measurements by providing calibration for orbiter remote sensing observations, which by necessity, involve model dependent inversion of the remote sensing data to obtain desired physical quantities.

The Galileo probe mission again illustrates the advantages of having both kinds of spacecraft in this context. As discussed in [7], prior to the Galileo probe encounter certain Earth based and Voyager spacecraft remote sensing observations of Jupiter's atmospheric composition were considerably in error with respect to particular key species.

For example, the Galileo probe measurements of helium abundance showed that the Jovian helium abundance as derived from Voyager was about 30% too low [11, 12]. Based on this result, a reassessment of the Voyager He mixing ratio for Saturn indicated that the Voyager value there was too low by a factor of 3-4 [13]. Voyager Jovian water abundance values, which pertained to regions within 5 μm hot spots, were found by the Galileo probe measurements to be in error by 1-2 orders of magnitude. This error is now thought to be due to a calibration problem with the Voyager IRIS instrument in the spectral region having wavelengths shorter than 5 μm [14]. In order to fit the Voyager IRIS data, an additional opacity somewhere between 3 and 8 bars is required. As another example, ground based and Voyager determinations of the NH_3 abundance indicated a C/N ratio about twice the solar value in Jupiter's atmosphere (cf. [7] and references therein), whereas the probe measurements indicated a C/N ratio less than or near solar [6, 10, 12]. This result represented a considerable change and a major surprise, one that affects proposed scenarios of Jupiter's formation and evolution. Each of these examples demonstrates the value of ground truth measurements.

On the other hand, the Galileo probe experience shows that a single vertical profile of measurements of particular quantities can be hard to generalize to the whole planet. Because of the probe entry into a 5 μm hot spot, the condensible species NH_3, H_2S, and H_2O behaved in very unexpected ways as a function of depth, as discussed earlier (see Fig. 4). If the Galileo orbiter had had instrumentation, such as a microwave radiometer to sound NH_3 and H_2O, the probe data could still have provided the necessary ground truth for retrieval of NH_3 and H_2O, and the orbiter could then have reliably sounded the deeper atmosphere and other latitudes and longitudes to obtain a comprehensive picture of the NH_3 and H_2O abundances.

3.3 Composition

We have already discussed how the Galileo orbiter-probe telemetry signal was used to derive the abundance of the key species NH_3 in the Jovian atmosphere. There are other important instances where measurements by both orbiter and probe(s) would pay handsome dividends for determining the composition of a planetary atmosphere. A few examples are given below.

One of the key questions regarding the composition of the Venus atmosphere is the abundance distribution of CO, because it is generally accepted that the oxidation state of the lower atmosphere of Venus is controlled by the net thermochemical reaction [15]

$$2CO + O_2 = 2CO_2$$

Fig. 5 illustrates the CO concentration as a function of height as implied by various remote sensing and in-situ observations. The CO mixing ratio evidently decreases with decreasing altitude below cloud levels near 65 km, although there is considerable uncertainty in the observations. As noted in the figure, cloud level CO concentrations have been derived entirely from Earth based infra-red remote sensing observations. Every probe to Venus has started taking in-situ measurements below 65 km because of entry considerations. If that is also the case in future probe missions, then remote sensing of CO at cloud levels from an orbiter becomes a very desirable objective, and is necessary if the global distribution of CO is to be obtained above the clouds where it is produced. Lower in the atmosphere, at altitudes between 35-45 km, a combination of Earth based remote sensing and in-situ measurements were used to obtain the CO mixing ratio. At the lowest altitude levels, only in-situ measurements of CO concentration exist [15].

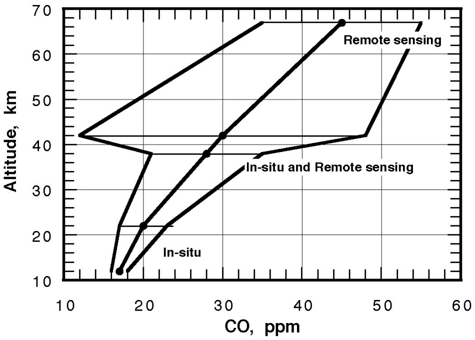

Fig. 5. Vertical distribution of CO in the atmosphere of Venus as determined from ground based and probe measurements. The middle curve shows the nominal velues, the range consistent with the measurement errors is given by the left and right curves. Based on data given in [15].

The abundance profile of CO is a good example of where the combination of in-situ and remote sensing observations can be used together to establish an important result. In future Venus missions involving both probes and an orbiter, it should be possible to completely nail down the CO distribution, both with respect to height and global position, but especially in the lowest atmospheric scale height. Once the entire CO distribution is accurately known, the chemistry of the atmosphere, and especially the chemistry between the atmosphere and solid surface, will be much better constrained. Clearly, remote sensing from an orbiter coupled with in-situ measurements from probes will be necessary to completely characterize CO and its chemistry.

Instrumentation that would be required to measure CO abundance would be an IR spectrometer on the orbiter, coupled with a GCMS and perhaps an IR spectrometer on the probe(s).

As another example of the benefit of simulatneous measurments from both an orbiter and probe(s), we consider the distributions of NH_3 and H_2O in the Jovian atmosphere. Referring again to Fig. 4, it can be seen that the Galileo probe was not able to determine the deep equilibrium mixing ratio of H_2O, although it did do so for NH_3 and H_2S within the error limits. The global abundance of H_2O is critical for developing understanding of giant planet formation and evolution (cf. [7] for discussion). Had the Galileo orbiter been equipped with a microwave radiometer, then using the probe measurements for ground truth, the radiometer data could have been used to derive the H_2O abundance deep in the atmosphere, as well as give a global picture of the H_2O distribution. Thus, in future Jupiter missions aimed at measuring atmospheric composition, entry probes coupled with an orbiter are highly desirable, and this is in fact the scenario recommended by the SSE Decadal Survey [3].

3.4 Winds

Obtaining the global distribution of winds in a planetary atmosphere is an area which requires close collaboration between an orbiter (or possibly flyby spacecraft) and probe. There are two aspects of this collaboration. First, sufficiently accurate tracking of probes necessary to determine winds to a resolution of about 1 ms^{-1} usually involves an orbiter or at least flyby spacecraft. Winds to this accuracy are usually necessary if one wants to understand the overall circulation. Second, in order to fit vertical profiles of wind determined from probe tracking into the context of the global circulation, orbiter measurements of global scale winds are required. These points can be illustrated by both the Pioneer Venus and Galileo experiences.

Fig. 6 illustrates the vertical profiles of westward and northward wind as determined from ground based differential very long base line interferometry (DVLBI) for each Pioneer Venus probe [16]. In this case the bus delivering all four probes was used to determine a reference trajectory which could be used to eliminate certain systematic errors in the probe wind determinations. Had this not been done, the accuracy of the winds from tracking the probes from Earth would have been significantly degraded. For example, eddy and mean meridional wind amplitudes at pressures greater than 1 bar, thought to be important for maintaining the superrotation, are of this magnitude in the deep Venus atmosphere.

Fig. 7 taken from [18], which shows the cloud level meridional winds obtained from tracking of cloud features by the Pioneer Venus orbiter, as well as the flybys of Mariner 10 and Galileo, illustrates the point that the global wind patterns at cloud levels, in which the probe measured winds were imbedded, could only be determined from global remote sensing.

Thus, in order to obtain good quantitative resolution on wind vertical structure (from probes) as determined within the context of global scale winds (from remote sensing), combining probes and orbiter measurements represents an optimal measurement strategy.

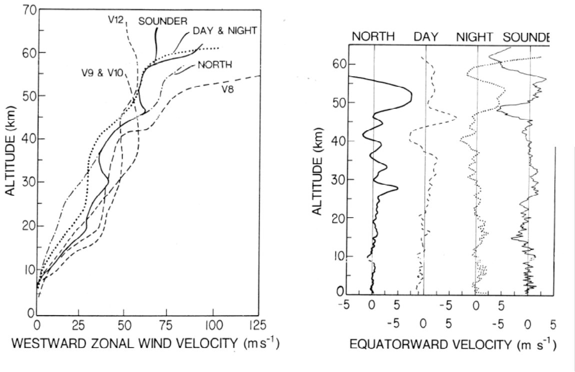

Fig. 6. Horizontal winds in Venus atmopshere as determined from tracking of the PV probes and Veneras 8-12. Taken from [16], [17].

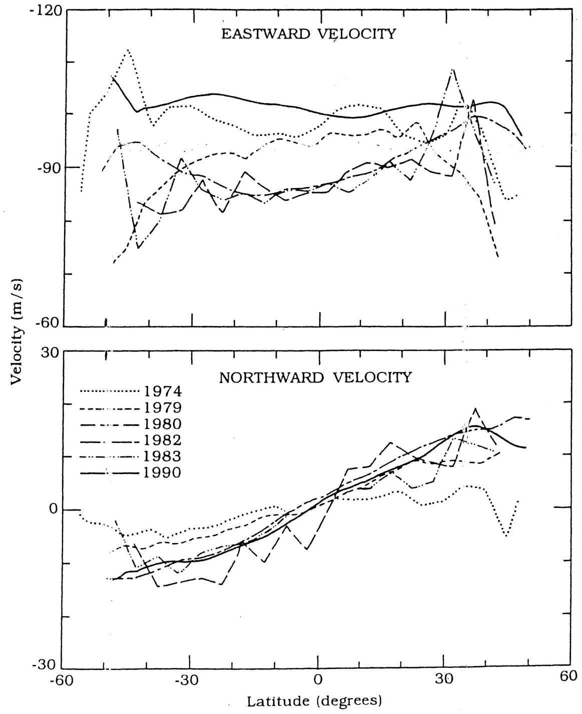

Fig. 7. Mean horizontal winds at cloud levels as determined from the PV orbiter, Mariner 10, and Galileo flyby. Taken [18].

The Galileo probe wind measurements illustrate why both probe and orbiter are required to adequately measure winds on the outer planets. Fig. 8 shows the winds measured by tracking the probe using two completely different tracking platforms. The upper curve gives the wind profile derived from tracking of the probe carrier frequency using the Very Large Array (VLA) set of radio telescopes [19]. As it turned out, the probe was visible from the VLA, and the probe carrier frequency (though not the full telemetry string) was detectable by the VLA. Thus, it was possible to obtain an independent determination of the Jovian winds from that obtained using the orbiter, a very valuable addition to the probe mission. However, by the time the probe reached about 4-5 bars pressure, absorption of the probe signal by ammonia through the long path length in the atmosphere caused loss of signal detectability from the VLA.

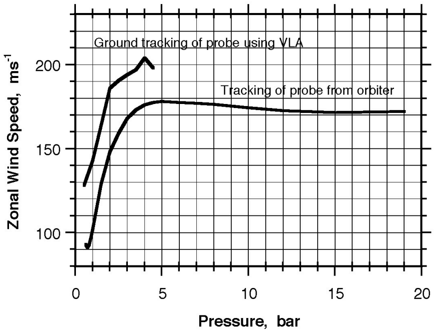

Fig. 8. Jovian zonal wind profiles at the Galieleo probe entry site as derived from Doppler tracking of the probe. Data taken from [19, 20]. See text for discussion of differences between the curves and uncertainties in the measurements.

The lower curve in Fig. 8 shows the wind as determined from Doppler tracking of the probe from the Galileo orbiter [20]. The two curves are qualitatively the same. The offset of 30-40 m s^{-1} between the VLA and orbiter-tracked winds would probably be significantly reduced if the VLA analysis was redone to incorporate the most recent determinations of probe descent velocity, which the VLA analysis uses at the beginning to derive the zonal wind profile. On the other hand, the winds near 1 bar are subject to significant error in the orbiter Doppler tracking method because of the almost vertical orientation of the orbiter-probe geometry, and derived values range from about 80 to 120 ms^{-1}.

The primary questions regarding the Jovian winds prior to the Galileo mission were how deep did the winds extend below cloud levels, and did they increase with depth. These are questions that apply to all the outer planets. The fact that the Galileo orbiter was able to track the probe to much deeper levels in Jupiter's atmosphere than possible from the VLA illustrates the advantage of tracking probes from orbiters when deriving winds for the outer planets. The geometry, in terms of long slant paths in the atmosphere for the probe signal to reach Earth, and the timing of having the ground based receiving station in view of the probe telemetry transmission at the right time to measure winds, conspire to make probe tracking from the ground for wind measurements rather limited. Long telemetry slant paths through the atmosphere limit wind tracking to shallow depths because of atmospheric attenuation due to clouds and signal absorbing trace species such as ammonia.

4.0 SUMMARY

We have discussed two catagories of probe-orbiter interactions which benefit the science return from a probe mission. The first category, "Mission Design Aspects", describes those aspects of mission design concerning an orbiter that can affect the science return from probe(s). The second category of probe-orbiter interaction is termed "Orbiter-Probe Science Interactions", and is meant to include interactions between oribter and probe(s) that directly involve science measurements made from each platform. We have shown, using the Pioneer Venus and Galileo missions as examples, how two mission related aspects of probe-orbiter interactions, delivery of a probe(s) to the entry site(s) by an orbiter, and communication between each probe and the orbiter, can considerably enhance the mission science return.

We also considered four general probe-orbiter science interactions that greatly enhance, or in certain cases are essential for, mission science return. The four topics are, global context of the probe entry site(s), ground truth for remote sensing observations of an orbiter, atmospheric composition measurements, and wind measurements. For each case particular examples drawn from Pioneer Venus or Galileo were identified that demonstrated the advantages of having probes and orbiters interact during a mission.

Future missions to Venus or the outer planets will probably have more ambitious goals than either Pioneer Venus or Galileo. Combining probes and orbiters in a mission design, and using each as observing platforms, seems to offer the greatest mission flexibility and science return to address these more ambitious goals.

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