SYNERGY BETWEEN ENTRY PROBES AND ORBITERS

Richard E. Young

(1) NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035 USA, Email: Richard.E.Young@nasa.gov

ABSTRACT

We identify two categories 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 orbiter 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 measurement 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 categories 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 orbiter 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.
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.

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.

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.
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
communication 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 accessibility 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 NH₃ by
inversion of the probe-orbiter radio signal amplitude as
a function 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 NH₃ is central
to understanding the evolution of Jupiter; second, there
was no other method that was capable of deriving the
vertical distribution of NH₃; and finally, the observed
NH₃ abundance profile behaved in a totally
unanticipated manner below the upper NH₃ ice cloud
deck (NH₃ 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 ≈
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 NH₃ 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).
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 illustrates the vertical profiles of the condensible species NH₃, H₂S, and H₂O 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, NH₃ abundance would have a constant mixing ratio below the NH₃ 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 NH₃, nor for any of the other condensible species with regard to their respective cloud condensation levels (note H₂S combines with NH₃ to form the NH₄SH cloud).

Furthermore, each species increased with depth below its condensation level at a different fractional rate than the others. Although NH₃ and H₂S were observed to eventually reach constant mixing ratios at depth, H₂O 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 NH₃, H₂S, and H₂O 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 NH₃ 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 NH₃, H₂S, and H₂O
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 NH₃ and H₂O, the probe data could
still have provided the necessary ground truth for
retrieval of NH₃ and H₂O, and the orbiter could then
have reliably sounded the deeper atmosphere and other
latitudes and longitudes to obtain a comprehensive
picture of the NH₃ and H₂O 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 NH₃ 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]

\[ 2\text{CO} + \text{O}_2 = 2\text{CO}_2 \]

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 values, the range consistent with the
measurement errors is given by the left and right curves. Based on
data given in [15].](image)

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
measurements from both an orbiter and probe(s), we
consider the distributions of NH₃ and H₂O in the Jovian
atmosphere. Referring again to Fig. 4, it can be seen that
the Galileo probe was not able to determine the
depth equilibrium mixing ratio of H₂O, although it did
do so for NH₃ and H₂S within the error limits. The
global abundance of H₂O 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$_2$O abundance deep in the atmosphere, as well as give a global picture of the H$_2$O 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 m$s^{-1}$ 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 atmosphere as determined from tracking of the PV probes and Veneras 8-12. Taken from [16], [17].](image)

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

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.

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 m s\(^{-1}\).

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 categories 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 orbiter 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.

5.0 REFERENCES