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Precision Landing on Mars Using Imaging Penetrator Beacons

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Analysis of a precision landing on Mars using penetrator beacons is presented. Penetrator beacons are small ballistic vehicles that would precede a soft lander to image a proposed landing region and establish a network of surface relative radio navigation beacons. A preliminary design of the charged coupled device imaging system mounted on the penetrator and investigations into the resulting size and resolutions of the images photographed by the imagers are studied. Investigations concluded that penetrator beacons could provide high resolution images of a landing region and provide a network of radio navigation beacons within the proposed landing region. A comparison between an orbiting facility and a single surface beacon navigation facility is performed and it is demonstrated that a surface beacon navigation is the preferred method to meet certain stringent mission navigation requirements.

Introduction

ONE of the most stringent requirements of future Mars exploration missions, both robotic and piloted, is to autonomously land a spacecraft in a very small area (approximately 10 m in diameter) that is clear of all surface hazards.[1–3] Landing footprint accuracies of 10 m will be required to guarantee that future Mars landers, such as the Mars rover sample return (MRSR) lander, with landing tracks 5–7 m across, have the capability of clearing hazards on touchdown. Rocks with diameters less than 1 m and surface slopes less than 15 deg over a 10-m baseline are mission requirements of the MRSR mission and are generally considered mission requirements for the lander's tolerance of surface hazards.[1–4]

Navigation based on Earth relative navigation sensors incorporate inertial map errors (tying the Earth inertial frame to the Mars landing site inertial frame) and cannot be used for real-time navigation due to the inclusion of inertial map error (on the order of several hundred meters) and the lengthy transmission times between the Earth and Mars. Furthermore, navigating from orbit to the surface of Mars using only an inertial measurement unit (IMU) will include drift rates, misalignments, etc., resulting in touchdown errors that exceed the touchdown navigation requirements. Therefore, a Mars relative navigation method will be required. Development of a real-time Mars relative navigation sensor for these autonomous precision landings can be very complex and costly, thus requiring designs that reduce mission costs and design complexity. It is proposed that the use of imaging penetrator beacons could support a precision landing, meet mission navigation accuracy requirements, and not require additional mission elements such as an imaging orbiter. The systems design of an imaging penetrator beacon is presented by the author.[5] The MRSR is used as a reference mission for this navigation investigation, but it is understood that the penetrator/beacon navigation method can be used for any mission requiring surface relative navigation. One of the main objectives of the MRSR mission is to gather interesting geological samples of Mars. Thus, the MRSR landing spacecraft will be required to land in an area that is scientifically interesting. Unfortunately, many of these geologically interesting regions on Mars have few safe (free of surface hazards) landing sites. This presents several navigation problems. Earth-based radiometric tracking [e.g., two- and three-way Doppler, ranging, very long baseline interferometry (VLBI), etc.] of the lander provides a very precise determination of the spacecraft state. However, these measurements are relative to the Earth inertial frame and not the Mars inertial frame which the Lander must use to perform Mars surface relative navigation. The difference between the two inertial coordinate frames (sometimes called inertial mapping error or frame tie error) for the MRSR mission is estimated to be 100 m which is orders of magnitude greater than the size of the predicted certified landing sites of 10 m (Ref. 6). Further, Earth-based tracking cannot provide real-time navigation information due to transmission time, information processing time, etc. Therefore, landing in a certified site within 10 m of a surface feature will require Mars surface-relative navigation capabilities.

As mentioned previously, many of the geologically interesting regions on Mars are in rugged terrain areas and may not meet the "safe" landing area requirements. The safe landing area is defined in Ref. 5. Basically, it is a 50 × 15 km (3-σ) landing area that contains a limited number of hazards such that there is a high probability of finding a 10-m landing area clear of hazards. This 50 × 15-km area is created by the fact that there is downrange and crossrange dispersions associated with the deployment and atmospheric entry of the penetrator/cluster aeroshell and penetrators. Looking for a site that meets the 50 × 15-km mission requirement (fewer hazards) could limit the type of the geological samples obtained. Therefore, the quality of the sample may depend on the range capabilities of the MRSR rover vehicle. Either a rover must be developed that is capable of traversing out of the safe landing region (if it is geologically uninteresting) or a safe landing region must be located which contains geologically interesting samples. Currently, there are two basic rover vehicles that are being considered for the MRSR mission.[7] A midrange rover capable of traversing 20–50 km and a long-range rover capable of traversing 100 km. Since the safe landing area is 50 × 15 km, the midrange rover may be restricted to remain within the safe landing area. However, the long-range rover will be able to depart the safe landing area and could travel into a more rugged area.

The penetrator/beacon navigation method uses surface feature navigation to remove the inertial map error. It also uses overlapping images to remove the relative map error. This approach would use the penetrators' onboard camera to photograph the landing area terrain during their descent, send this image information back to Earth via an orbiting lander relay, and allow Earth-based ground controllers to select a suitable landing site within the images. The selected landing site information is relayed back to the lander in the form of distance and bearing from the rf beacons mounted on the penetrators to the selected landing site. The penetrator imaging data will be

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used to produce cartographic map products, which include topography, boulder sizes, and the distribution and location of other hazards in order to assess the relative safety and traversability of various landing sites. The penetrator/beacon navigation method does not require the real-time, high-speed, computation of the hazard avoidance methods and does not require the secondary orbiting vehicle or large amounts of high resolution images of current precision landing mission designs. This investigation discuses this possibility and presents a preliminary mission design of the penetrator/beacon navigation method including analysis of the MRSR lander vehicle landing accuracies using a single penetrator/beacon for navigation. MRSR lander navigation accuracies using more than one of the four surface navigation beacons is currently under investigation and is not included in this study.

Penetrator/Beacon Navigation Station Deployment

A detailed investigation into the systems design, and the deployment, entry, and impact of the penetrator/beacons can be found in Ref. 5. The following is a summary of that investigation. The penetrator/beacon scenario begins after the landing spacecraft has established orbit around Mars. Prior to separation, the penetrator cluster containing the penetrators will be attached to the lander spacecraft via the penetrator terminal decelerator shell. The cluster aeroshell will be deployed from the lander spacecraft will initialize its attitude and then fire its spin thrusters to start the vehicle spinning in order to spin stabilize it for the deorbit maneuver. It then conducts a deorbit burn that sends it toward entry interface (defined as 125 km above ground level). The cluster aeroshell proceeds through the atmosphere and, at 15 km above the surface of Mars, a parachute is deployed to decelerate the penetrator cluster and separate the the penetrator cluster from the aeroshell. At 13-km altitude, the penetrator deployment springs will simultaneously eject the penetrators out and away from the penetrator mounting cluster, and the penetrators will deploy their individual parachutes. The penetrators will be mounted 90 deg apart on the penetrator mounting cluster and thus will have an initial relative motion of 90 deg away from each other on deployment. Finally, at 10 km above the surface, the penetrator parachutes are jettisoned, and the penetrators are allowed to free fall to the surface which results in an impact velocity of approximately 110 m/s. Illustration of the penetrator/beacon entry/landing scenario can be found in Ref. 5.

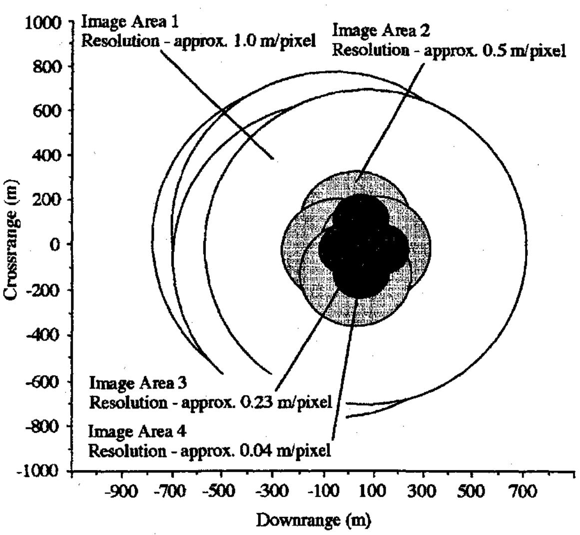

Fig. 1 Four areas imaged by all four penetrator cameras.

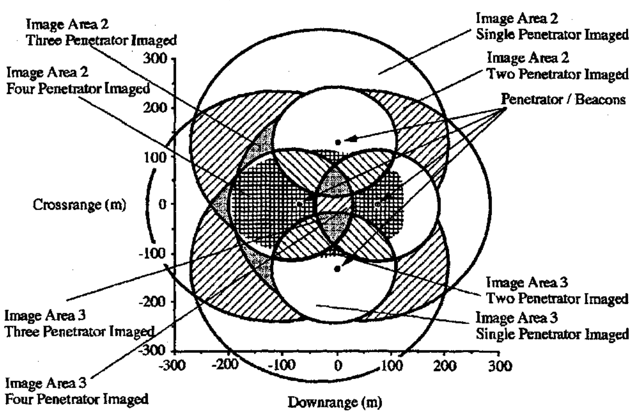

Fig. 2 Last two areas imaged by all four penetrator cameras.

Each penetrator will be carrying a charged coupled device (CCD) imaging system in its nose as shown in Fig. 5 of Ref. 5. Approximately 100 s after penetrator ejection from the penetrator mounting cluster the penetrators will begin to image the surface below them. Because the penetrators stay within 250 m of each other and their fields of view (FOV) are large, the penetrators will image common overlapping surface areas. The total area imaged by all four penetrators will vary from about 1.5 km^2 for the first image at a resolution of approximately 1.0 m/pixel to 1600 m^2 at a resolution of 0.04 m/pixel for the last image. Figures 1 and 2 show common areas imaged by the penetrators cameras during descent. This will provide mission planners with detailed surface maps of the MRSR landers' safe landing region.

The penetrators will impact the surface of Mars within the imaged area; and through analysis and trajectory reconstruction, using stored accelerometer and radar altimeter data, the location of the penetrators relative to the imaged landing sites will be well known. Each penetrator will carry a communications system (beacon) capable of supplying radio frequency ranging to a landing vehicle. The penetrator will store all measurement data on board the penetrators' mass storage, and transmit the stored data to the lander in orbit at a later time.

Analysis of Penetrator Imaging During Descent

Imaging Requirements and Performance

One of the most important aspect of the penetrator/beacon mission will be the imaging performed during the descent to the surface. Each penetrator will have a CCD camera mounted to its nose. Each penetrator will acquire four images of the surface within altitudes ranging from 3 km to 100 m above the surface. A standard size CCD imaging system with an array 1000 $\times$ 1000 pixels was assumed for this investigation. This provides approximately 1 $\times$ 10^6 pixels per image. At 8 bits per pixel (for 256 grey scale images), each image will require 32 Mbits of memory. A 2:1 compression utility will be utilized to reduce the amount of memory required by 50%. This results in a total memory requirement of 16 Mbits plus additional memory for accelometer and radar altimeter measurement data. Because power is only required when storing or dumping information, bubble memory will be used to store the images to reduce power requirements. The four images accumulated by each penetrator will be acquired approximately 10, 6, and 4 s apart. Therefore, each image will need to be stored within 3 s (allowing 25% margin and overhead) to prevent overlapping of the incoming image data. This will require a memory input rate of approximately 2.7 Mbits/s (including image compression). Storage rates of the accelerometer and radar altimeter sensor are much lower (approximately 80 bits/S for 0.1 s measurements) because there is much less data to store.

An approximation of the resolution of the image can be determined by dividing the total imaged area by the number of available pixels. The penetrator camera was estimated to have an FOV that spans 25.0 deg of arc, a focal length of 15 cm, an angular resolution of approximately 0.44 mradians/pixel, and an integration time of 0.5 ms for 80% saturation. Under these assumptions, the last three images taken during penetrator descent meet mission requirements of 0.25 m/pixel. The first and last image, taken at resolutions 1.5 and 0.002 m/pixel, respectively, will aid in the process of obstacle identification as well as penetrator trajectory reconstruction. Figure 3 shows the camera resolution as a function of altitude and camera FOV. It can be seen that an FOV of 50 deg offers the greatest imaged area but does not meet the mission requirements of 0.25 m/pixel. Also, to have at least two sets of images meeting this requirement, the FOV must be less than 25 deg. Therefore, a FOV of 25 deg was selected because it offered the greatest imaged area that produces at least two overlapping images and also met image resolution requirements. Figure 4 depicts the minor axis of the image ellipse as a function of altitude and camera field of view. This figure shows the limitations imposed on the imaged area by restricting the camera field of view to 50 deg or less. Based on the resolution and the area imaged, it was decided that the field of view would remain 25.0 deg for the penetrator imaging cameras.

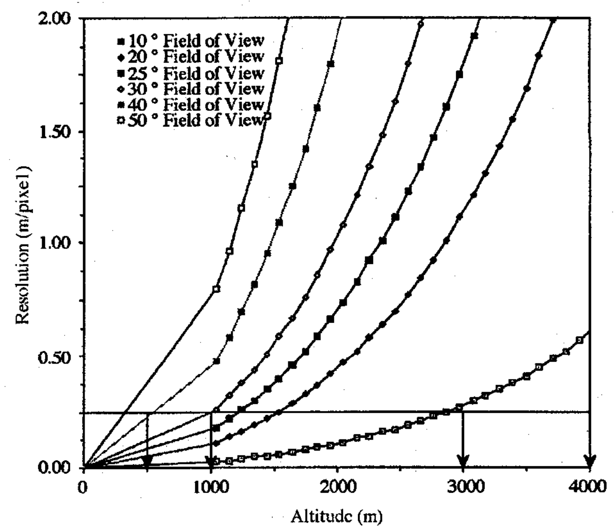

Fig. 3 Image resolution as a function of altitude and camera field of view for a 1 × 10⁶ pixel CCD array.

Object height will be measured according to obstacle shadow size, surrounding slopes, and the known angle of the sun. To measure the average slope across a smooth landing site, the site needs to have at least three surrounding objects of sufficient size so that they, or their shadows, can be observed. By viewing the objects (or their shadows) stereoscopially, the slope of the area can be estimated. Using stereo-binocular imaging will involve acquisition of the images simultaneously from sensors separated by a known baseline distance. For stereo-binocular imaging to work successfully, maximizing the length of the surface features' shadows is important. Maximizing shadows should be considered an important mission requirement and will influence penetrator deorbit inclinations and touchdown longitudes.[8]

The stability of the penetrator CCD imaging camera during descent has a direct influence on the quality of the images. Penetrator rotation, pitching, yawing, and descent rates will all play a major role in camera pointing which effects the quality of the images. Scale changes caused by large variations in assumed imager altitude at the time the picture is taken can lead to failure in correctly identifying a landmark. This sensitivity to errors, based on knowledge of the lander altitude, will be reduced since a radar altimeter is included in the penetrators' baseline design.

Because the penetrators may possibly rotate during their descent, the actual surface area imaged by the CCD camera was calculated as an ellipse rather than a parallelogram. Figure 5 shows the definite imaged area of one scout beacon having a 25-deg field of view. It was assumed in this study that the major axis of the ellipse was a function of both the flightpath angle and the altitude, whereas the minor axis was only a function of altitude (no sideslip angle was assumed). Figure 8 displays how the FOV for a single penetrator varies from the time of ejection through the time that the last image is acquired. The first image covers nearly 1.5 km^2, and the last image covers approximately 1600 m^2. When the FOV of the penetrators are superimposed, a common field of view can be obtained as is shown in Figs. 1 and 2. These figures graphically demonstrate how much common area is imaged by all four penetrators.

Reconstruction of Terminal Images for Relative Penetrator Positions

As explained earlier, for the penetrators to provide useful images, a method for gathering altitude information during the

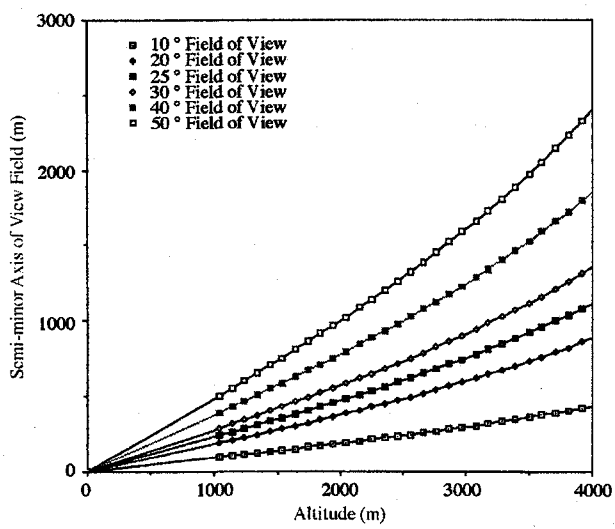

Fig. 4 Semiminor axis of view field a function of altitude and camera field of view for a 1 × 10⁶ pixel CCD array.

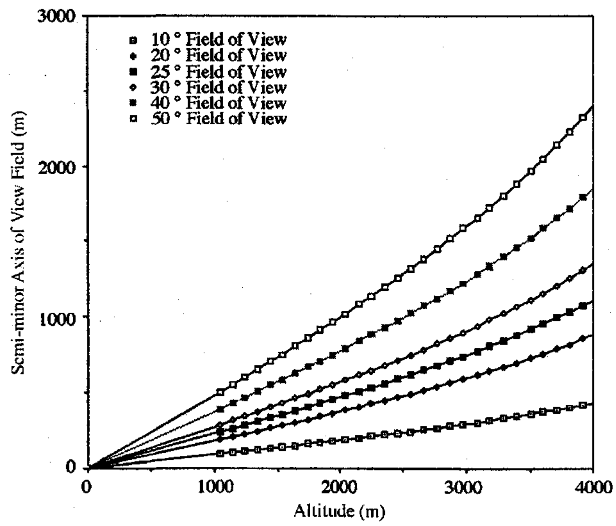

Fig. 5 Definite image area of one scout beacon with 25-deg field of view.

trajectory must be provided to the penetrators. A radar altimeter will be mounted on the penetrators and will provide altitude data for each image taken during the descent. The altimeter antenna will be mounted on the body of the penetrator such that the nominal trim angle combined with the relative flight path angle is near 90 deg, thereby keeping the altimeter antenna aligned with the local vertical.

Two sets of accelerometers will be utilized. One set will be mounted at the center of gravity (c.g.) and the other set in the forward position of the penetrator, shown in Fig. 5 of Ref. 5. Attitude during the descent will be measured using the accelerometers as they sense angular acceleration about the c.g. of the penetrator. Using the two sets of accelerometers and knowing the position of the accelerometers on the penetrator will aid in uncoupling translational accelerations from angular accelerations. Integration of these uncoupled accelerations, angular and translational, will give penetrator position, velocities, and attitudes. Wind gusts that effect the penetrator's trajectory will be sensed by the induced aerodynamic accelerations on the penetrator. If the penetrators are in a constant moving air mass, it will be depicted in the images.

Combining accelerometer calculated state data with radar altimeter measurements and the image data will fix the surface impact position of the penetrator. Additional aid in locating the relative positions of the penetrators with respect to each other, including fixing the orbiting lander inertial frame to the penetrator inertial (surface relative) frame, could come from the lander ranging to the penetrators from orbit. This is currently under investigation and was not considered in this investigation.

The last penetrator images will be at 100 m and will cover a circular area on the surface of Mars with a radius of approximately 20 m. Fixing the impact position of the penetrators within the last image (20-m radius) is currently under investigation. The overlapping areas of the other three images will also be used in the trajectory determination for each of the penetrators and aid in determining their impact points through surface feature comparison and orientation of shadows. The lander navigation site will be fully established once the penetrators have been located in their images and with respect to each other. Preliminary results indicate that the impact position errors should be no greater than 1–2 m using all available information for reconstruction.

Lander navigation will consist of ranging off of three or more beacons where the forth beacon can be used as a backup. The intersection of circular arcs traced out by the beacons target radial magnitude will intersect at the lander's target touchdown point. Figure 6 shows the navigation of lander with respect to penetrator beacons. Preliminary investigations (to be published along with the penetrator impact point error analysis) indicate that this geometric reconstruction of a pseudolanding target position based on three known beacon positions should easily meet mission requirements. Preliminary analysis shows that initial surface orientation of the beacon cluster with respect to the lander orbit plane will not require extreme accuracies given that the relative position of the beacons with respect to each other and the local terrain is well established. However, uncertainty in the beacon navigation plane (surface mean sea level altitudes) could yield inaccuracies. One possible solution to this problem would be to mount a camera on the afterbody of the penetrator which would provide the opportunity to study the surface surface slopes and features of Mars and aid in determining the direction of the other penetrators after they have impacted the surface.

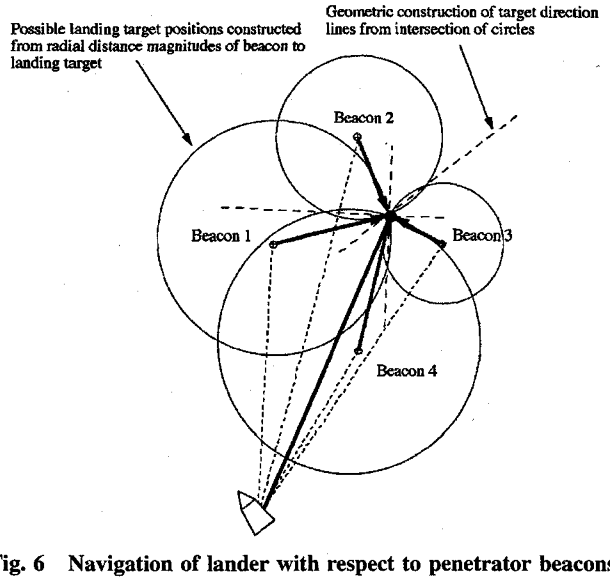

Fig. 6 Navigation of lander with respect to penetrator beacons.

Navigation Analysis and Comparison

Mars Rover Sample Return Lander Reference Mission Scenario

Separate assessments of terminal landing navigation errors, using either an orbiting beacon (possible on an additional spacecraft separate from the lander) or a single surface beacon, was performed for the MRSR entry and landing scenario. Figure 7 shows the MRSR entry and landing scenario. The three-degree-of-freedom (3-DOF) simulation was implemented and included the following guidance options/phases of the MRSR mission: 1) The entry guidance uses a Mars predictive equilibrium guidance (MPEG) algorithm that guides the entry vehicle along an equilibrium glide trajectory designed to satisfy a set of equality and inequality constraints at chute deployment.[9] An equilibrium glide assumption permits analytical prediction of the terminal state conditions. 2) The approach phase uses an azimuth controller similar to the one used in the Space Shuttle terminal area energy management (TAEM). The main function of the azimuth controller is to guide the vehicle's velocity vector into the local vertical plane of the landing site. The controller computes the current vehicle velocity vector and the vertical plane to determine the azimuth angle between the two vectors. The difference is multiplied by a gain to determine the new commanded bank angle. 3) The parachute phase models a ballistic parachute. There are no active controls used during the parachute phase. Therefore, the method used to control the ranging of the chute is to control the altitude of chute deployment and jettison. 4) The terminal phase uses a derivative of the explicit guidance (E-Guidance). It solves a two-point boundary value problem constraining the downrange jerk, given the initial and terminal conditions. It also implements a routine to limit the thrust forces and gimbal angles of the lander jets.

This analysis was performed only for comparison of orbiting and surface ranging navigation and does not include multiple beacons that will be provided in the actual design. Multiple beacon investigations are currently under investigation and will also include investigations into other types of measurements such as Doppler, integrated Doppler, etc. The MRSR lander

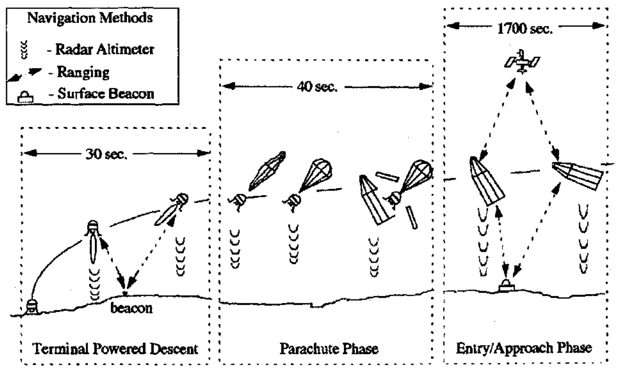

Fig. 7 MRSR entry/landing scenario.

was assumed to have a mass of 4000 kg and a lift-over-drag ratio (L/D) of 1.0.

Navigation Method and Scenario

A linear covariance analysis was used to propagate the navigation error statistics along a reference trajectory. Sensor measurement updates every 40 s were incorporated using a full state extended sequential Kalman (EKF) filter to obtain the minimum error covariance. It should be noted that a full state filter is not realistic for onboard implementation and a suboptimal (reduced-order) filter will be required for onboard processing. The primary navigation sensor used continually during the entry and landing is the IMU. Secondary sensor suites consists of rf ranging augmented with radar altimeter measurements. The MRSR landing scenario is depicted in Fig. 7, and Table 1 depicts the descent, landing timetable, and events. Because rf ranging requires the transmitter to be within the line of sight, line-of-sight requirements were investigated and are depicted in Figs. 8 and 9. The orbiting beacon was constantly in sight although navigation updates, using the surface beacon, could not be used until the lander was within 450 km of the surface beacon.

Table 1 MRSR descent and entry timeline

	Days:h:min
Comm. orbiter/lander tracked by deep space network while quiescent	−2:00:00
Initial state and navigation covariance uplinked from (DSN)	−1:00:00
Align lander IMU using comm. orbiter star tracker	0:00:00
Separation of lander and comm. orbiter	0:00:00
Deorbit burn, ΔV 115 m/s	0:00:00
Coast	——
Comm. orbiter beacon lock-on (option 1)	0:00:05
Entry interface, 125 km	0:00:38
Entry guidance active, 0.05 g	0:00:42
Entry	——
Surface beacon lock-on (option 2) 540 km DR, 38 km alt	0:01:04
Parachute deployment, 5 km	0:01:11
Parachute jettison, 1.5 km	0:01:12
Terminal descent engines active, 1.5 km	0:01:12
Landing	0:01:14

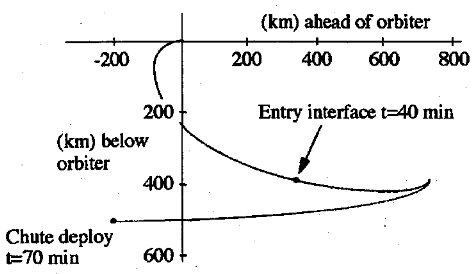

Fig. 8 Relative motion of lander with respect to orbiting beacon.

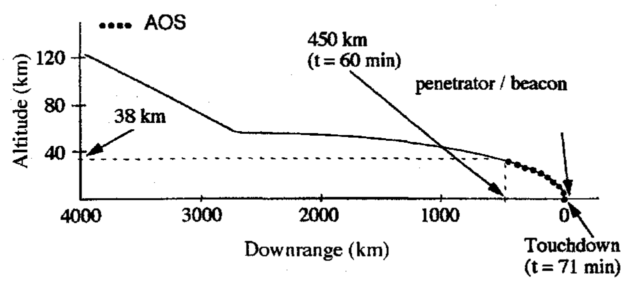

Fig. 9 Relative motion of lander with respect to surface beacon.

The first navigation scenario investigated is the MRSR lander entry radiometric measurements from an orbiting vehicle in a 500- × 500-km orbit carrying an rf beacon. It is assumed that the lander is attached to this orbiting vehicle (such as a communications orbiter) until just prior to the start of the deorbit sequence. Because the vehicles are connected, their initial inertial state vectors are identical, and there is no relative state error between them. The lander inertial measurement unit is aligned just prior to separation. It is assumed that the other orbiter vehicle, serving as the navigation aid, will remain quiescent (no significant translational acceleration) throughout the lander's deorbit/entry phase so as not to deviate from the trajectory that the lander navigation system assumes it will take.

The second navigation scenario investigates a single, surface fixed, rf beacon that will be mounted on a penetrator. The penetrator's rf beacon uses two-way ranging which is generated when the lander's receiver measures the number of cycles of radio Doppler frequency flown through, along the signal from the Lander to the station and back. This offers very accurate range change measurements, does not require the penetrator to carry an onboard clock (which is required in one-way ranging), and does not require station frequency knowledge. Another advantage of using a two-way rf surface beacon over a one-way rf surface beacon is the emphemeris of the surface beacon does not need to be broadcast on the signal since the penetrator/beacon remains fixed to the surface.

Note, not considered in this study is the possibility of placing other beacons uprange of the lander's trajectory, thus making it possible to always have surface beacon navigation. However, if the images of each of the additional surface beacons do not overlap (which is highly probable) there will be a relative map error in relating the inertial coordinates of the beacons.

Initial Conditions Used in Navigation Analysis

Initial navigation errors used in the navigation simulation model include the following 1-σ values. The error model of the IMU is given in Table 2. The initial covariance of the lander prior to its deorbit burn is based upon the Mars observer mission and is given in Table 3.[1] The values of the initial covariance matrix used for the orbiter carrying the rf beacon is from the MRSR mission communication orbiter design and is also given in Table 3.

Results of Navigation Analysis

Results of the navigation analysis are show in Table 4. One can see that the surface beacon removes the inertial map error thus meeting mission requirements. The orbiting beacon does not meet mission requirements because of the inertial map error

Table 2 IMU error model

Accelerometer error (H-750 LINS stapdown IMU type)
3 Axis—accelerometer bias: (1.0E-05, 1.7E-05, 5.0E-05) m/s^2
3 Axis—accelerometer scale factor: (70, 70, 350) ppm
Sensor measurement error
Range measurement bias: 5 m (surface and orbiting beacon)
Range measurement white noise: 0.1 m (surface and orbiting beacon)
Radar altimeter measurement bias: 5 m (surface and orbiting beacon)
Radar altimeter measurement white noise: 0.1 m (surface and orbiting beacon)
Unmodeled noise
3 Axis—unmodeled system acceleration white noise: 5.0E-08 m/s^2
Inertial map frame tie error
3 Axis—inertial map error bias (100, 100, 100) m

Note: The IMU alignment, accelerometer bias, and scale factors currently model a platform IMU; results will change somewhat when modeling a strapdown IMU. Map error uncertainty is based on deep space network (DSN) observations of the MRSR lander while in orbit around Mars.[6]

Table 3 Initial covariance matrices for lander and orbiter

Alt, m	Downrange, m	Crossrange, m	alt rate, m/s	Downrange rate, m/s	Crossrange rate, m/s
			Lander		
187.6000	−0.6780	−0.1510	0.6560	− 0.9990	−0.1220
0.0000	1031.3000	0.1210	0.9990	0.6680	0.0460
0.0000	0.0000	291.6000	−0.1170	0.1480	−0.1280
0.0000	0.0000	0.0000	0.8300	−0.6460	0.0510
0.0000	0.0000	0.0000	0.0000	0.1500	0.1280
0.0000	0.0000	0.0000	0.0000	0.0000	0.1200
			Orbiter		
24.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	260.0000	1200.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.1800	0.0000
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0017	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0320

Note: Off diagonal terms are the cross correlation coefficients.

Table 4 Navigation analysis results

Option	Downrange, m	Crossrange, m	Altitude, m	RSS, m
1) IMU only	2962.7	4228.1	3016.2	5979.2
2) IMU + orbiting beacon	655.3	980.9	15.8	1179.8
3) IMU + surface beacon	1.8	3.1	1.2	3.8

Note: Options 2 and 3 include the use of a radar altimeter.

contributing to a final rss error of approximately 1300 m. When neglecting the inertial map error, navigation accuracy is most affected by the initial covariance, IMU misalignment at deorbit, and subsequent drift. Also, due to the geometry of the problem (parameter correlation), the range measurements yield information primarily about the altitude and downrange channels while heading straight to the target. However, the crossrange channel improves once significant crossrange is developed during the entry roll reversals of the lander. This makes the crossrange more observable. Errors not included in this study, which need to be addressed at at later date, are Mars gravity errors, errors in the Mars spin axis, navigation analysis blackout, moving antenna (vehicle) with respect to center of gravity of vehicle, and detailed range limits/observability.

Areas Requiring Further Investigation

The following are several areas that remain to be addressed, or are currently under investigation, that pertain to the penetrator/beacon surface navigation method. Some of these were addressed earlier in this paper and are restated for clarity.

1) The navigation analysis presented in this paper was for comparison of orbiting and surface ranging navigation only, and does not include the influence of multiple beacons that will be provided in the actual design. Multiple beacon investigations are currently underway and will also include investigations into other types of measurements such as Doppler, integrated Doppler, etc.

2) Using lander ranging to the penetrators from orbit as an additional aid in locating the relative positions of the penetrators with respect to each other, including fixing the orbiting lander inertial frame to the penetrator inertial (surface relative) frame, warrant investigation.

3) Preliminary investigations indicate that the geometric reconstruction of a pseudolanding target position based on three known beacon positions should easily meet mission requirements. The initial surface orientation of the beacon cluster with respect to the lander orbit plane should not require extreme accuracies given that the relative position of the beacons with respect to each other and the local terrain is well established. However, uncertainty in the beacon navigation plane (surface mean sea level altitudes) could yield inaccuracies. One solution to this problem would be to mount a camera on the afterbody of the penetrator which would provide the opportunity to study the surface slopes and features of Mars and aid in determining the direction of the other penetrators after they have impacted the surface.

4) Errors not included in this study that will need to be addressed at at later date include Mars gravity errors, errors in the Mars spin axis, navigation analysis blackout, moving antenna (vehicle) with respect to center of gravity of vehicle and detailed range limits/observability.

Conclusions

One of the most important benefits of the penetrator/beacon navigation methods is that it provides a low-cost precision landing navigation method that meets the stringent navigation requirements of future missions. The employment of penetrator/beacons will provide the ability to perform a precision landing for little cost and minimal technical development. Because the penetrator has provided high resolution imagery of the landing site, the landing vehicle would not be required to have a complex hazard detection and avoidance system, thus simplifying the system design and improving the chance of mission success. The penetrator would also provide low and high resolution imagery of the proposed landing site and its surrounding area. This data would be invaluable to mission planners, for the selection of suitable landing sites and for the generation of detailed surface maps which could be used in designing the traverse paths for roving vehicles and manned exploration. The images from the four penetrators could be combined to form stereo-images generating even more detailed information about the proposed landing region. Finally, the combination of penetrators and a Mars lander are completely self contained; there is no reliance on any other vehicle or system.

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