VELOCITY ESTIMATION OF A WIND-DRIVEN MARTIAN BALLOON

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The Mars '96 mission will place a balloon probe into the atmosphere of Mars. The instruments onboard the balloon will include a meteorological package, surface sensors, and four cameras to provide images of the Martian surface, The balloon is intended to fly during the day and descend to the surface at night. This work describes a technique that uses pairs of overlapping images of the surface, altimeter measurements of the balloon's height, and measurements of the azimuthal position of the sun to estimate the velocity of the balloon during the day. Because the low power of the balloon telemetry system limits the number of images that can be transmitted to Earth via an orbiter link, processing of the images must be completed onboard the balloon.

In order to determine the expected accuracy of the Martian balloon velocity, a model balloon trajectory was used to produce a sequence of simulated surface images. The effects of expected rotational and swinging motions of the balloon camera were also introduced into these images, A simple algorithm was used to determine the offsets between pairs of these images. The image offsets and simulated altimeter measurements were input to a Kalman filter/smoother to provide estimates of the balloon velocity and its uncertainty,

INTRODUCTION

Balloon borne meteorological probes, or radiosondes, have long been used to measure the properties of the Earth's atmosphere from near the surface to high altitudes. Balloon probe measurements of the pressure and temperature profiles and atmospheric composition have provided, and continue to provide, much of the data used in development of global atmospheric models. Tracking the motion of a balloon provides a direct measurement of wind velocities on both a local and global scale over a range of altitudes. Their low cost and relative simplicity make radiosondes an important tool in the study of the Earth's atmosphere even in this era of Earth orbiting remote sensing satellites.

For these and other reasons, balloons also offer an attractive means of studying the atmospheric properties and dynamics of those planets in our solar system which possess substantial atmospheres. Unlike planetary landers or atmospheric probes such as those of

but the limited periods of mutual visibility severely restrict the frequency and duration of these measurements.

Earth based techniques

During the VEGA mission, the proximity of Venus to Earth and the available signal power from the balloon probe transmitters allowed their positions to be directly measured by Earth-based radiometric tracking of the telemetry signals broadcast by the balloons. However, in the case. of the Mars '96 mission, the limited power and short broadcast peri-

Day   **Night**

Balloon envelope, 30 kg (incl. Helium)

42 m

50 m

Camera and meteorological instruments, 20 kg
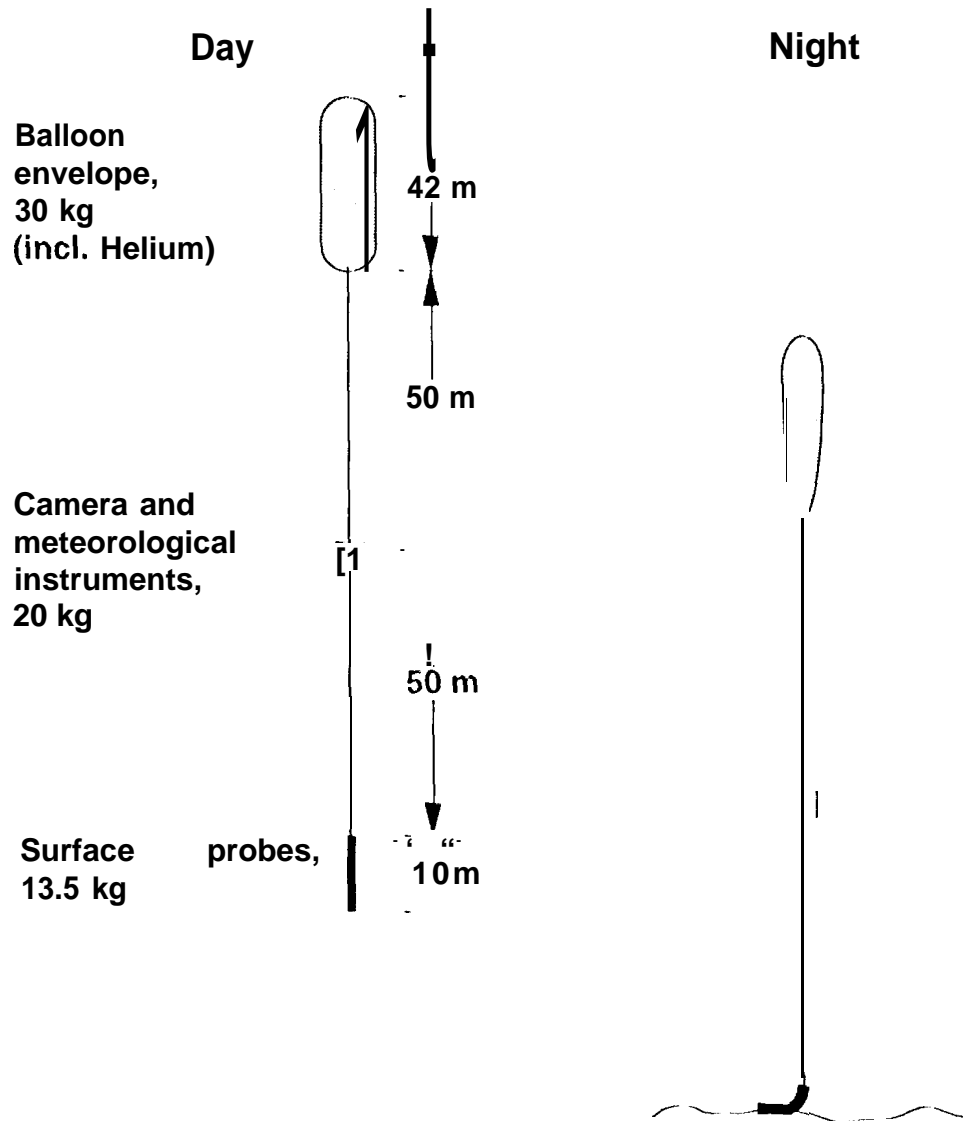
[1

50 m

Surface   probes, 13.5 kg

10 m

Figure 1. Schematic diagram showing the dimensions of the Mars '96 balloon/gondola/surface probe configuration. At night the balloon will descend to the surface where the instrumental "snake" will make measurements of surface properties.

mate the balloon motion. The images used in these studies were generated synthetically since no images of the Martian surface are available with the resolution expected from the balloon cameras. The software that generates these synthetic images uses a fractal based technique and attempts to simulate the actual geophysical processes responsible for the surface features[8]. Figure 2 shows examples of two synthetic images from a balloon at an altitude of several kilometers using the lowest resolution camera onboard the balloon.
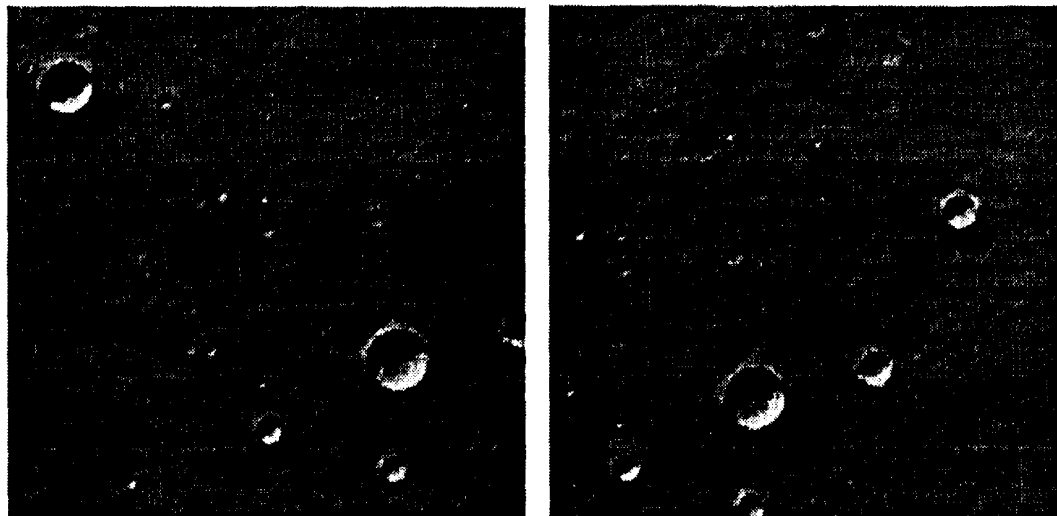

Figure 2. Simulated images of the Martian surface. These two images correspond to a balloon altitude of approximately 3 km and assume a camera focal length of 6 mm. The right hand image is a shifted version of the left hand image.

Image registration algorithm

'There are many different algorithms available for determining the offset of a pair of images. IicatLlre-based techniques attempt to locate individual features (hat arc common to the two images, If a sufficient number of these common features can be identified, the motion of the camera can be uniquely determined provided that independent information of the depth or range to the objects is available.g. Simpler methods measure the. correlation function between the two images by computing the cross power spectrum of the Fourier transform of the two images. If this correlation function is divided by its magnitude one obtains the phase correlation of the two images[10]. This function contains all of the information on the relative displacement of the two images and is relatively immune to variations in the image intensity that might otherwise lead to an incorrect identification of the. peak in the correlation function.

To improve the efficiency of the image matching algorithm a hierarchical algorithm was used where the two images arc first put through a low pass filter and the correlation function is computed for these lower resolution, and hence smaller, versions of the images. A coarse offset of the two images determined in this step is then used to select smaller areas of the original images which, from the results of the first step, arc known to contain common information. The image shift computed from correlation of these higher resolution sub-images is then added to the. coarse. shift computed in the first step to provide the final estimate of the image offset, Fig.3 shows a schematic diagram of this algo-

rotation between images is a result of the natural tendency of the balloon (and the attached camera) to rotate during flight. Changes in the altitude of the **balloon** during its flight effectively change the relative scale of the images. The small amplitude pendulum-like swinging motion of the balloon dots not in itself affect the ability to match the. images, as do the rotation and scale differences, but it dots introduce an apparent trans - lational motion that causes a systematic error in the estimated wind velocity. The magnitude of this effect will be discussed in the next section,

in order to assess the extent to which rotation and scale differences between images affect the accuracy of the image registration algorithm, a number of synthetic images were generated with known values of relative rotation and scale and known translational Offset The image shifts were computed for pairs of these images and the estimated im- age shifts compared to the true value. Figure **4 shows** the results for image rotation, and Figure 5 shows the equivalent results for relative scale change due to changes in the bal- loon altitude.
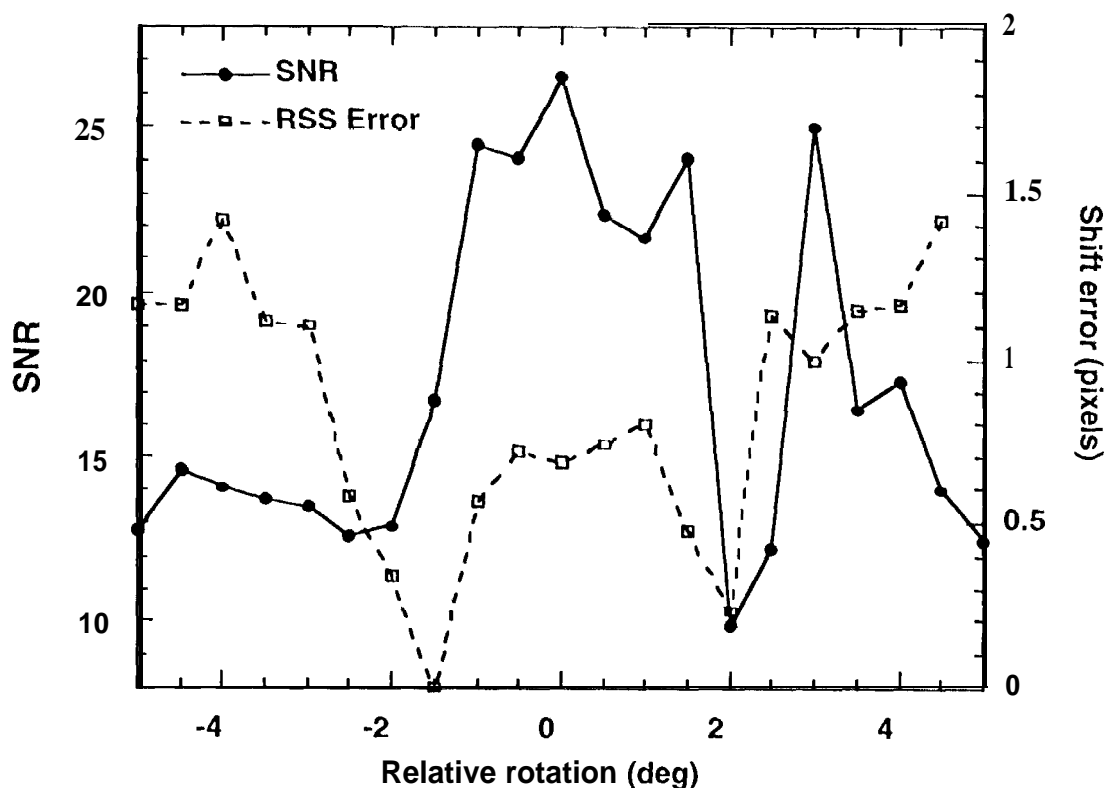

Figure 4. Effect of relative image rotation on the accuracy of the image shift de- termined by the image registration algorithm described in the paper. The open squares give the difference between the true shift and the shift estimated from the position of the peak of the correlation function. The dark circles show the signal to noise ratio of the correlation peak

Our method of velocity estimation assumes that the sun sensor onboard the balloon will be able to provide information on the relative rotation of the. balloon between images that will allow the images to be corrected for this rotation with an accuracy of approxi- mately **0.5** deg prior to correlation. From Fig. 4 it is seen that a relative rotation of this

VELOCITY ESTIMATION

The Mars '96 balloon is designed to fly during the day and descend to the surface at night when the instruments contained in the "snake" will make measurements of surface properties. After sunrise the balloon will again rise to a cruise altitude of 2.5-4.0 km where it will remain until the next night when it will again descend to the surface. In this work, however, only the "cruise" phase of the balloon flight will be considered. The rapid changes in altitude during rise and descent make the image matching much more difficult. in addition, the amplitude of the swinging motion of the balloon camera is expected to be much greater during the ascent phase which, if uncorrected, would add a significant systematic error to the estimated velocity.

Estimation of horizontal wind velocities during ascent or descent may be possible using more sophisticate.d image processing algorithms or with the addition of sensors that accurately measure the deflection of the balloon camera from true vertical. Another possibility is to record a larger number of images during the ascent or descent phases and attempt to estimate the parameters of the swinging motion of the balloon along with the desired horizontal velocity. Images from the three other cameras onboard the balloon might be useful in this case. At the present time it is uncertain whether the final configuration of the balloon instrument package will allow either of these approaches.

The range of balloon speeds that can be measured with images of the Martian surface is limited by several factors. Obviously, in order to register two images, they must contain common information, and this sets an upper limit on the time interval between images. This interval must be short enough to insure that there is some overlap between the images. If the interval is too long, the balloon will have drifted too far and the two images will contain no common information. The length of this interval depends on the wind velocity, the altitude of the balloon, the focal length of the camera, and the size of the image array, and is given by the formula

$$V_{max} = \frac{h\eta_p \Delta p}{\Delta t f} \tag{1}$$

where **h** is the height of the balloon, η_p is the separation between pixels of the CCD array, **Δp is** the maximum allowed shift in the two images measured in pixels, **Δt** is the time separation between the two images, and **f** is the focal length of the camera system,

The inherent accuracy of the image matching algorithm of 0.5- 1,0 pixel determines an altitude dependent lower limit on the velocity accuracy. A more serious effect on the accuracy of the estimated wind velocity is due to the swinging motion of the balloon camera As shown in Fig. 6, depending on the period and amplitude of the swinging motion and the time separation between the images, there will be an *apparent* contribution to the motion of the balloon that is due to a difference in the deflection of the camera from the true vertical at the times that the images are recorded. If nothing is done to account for this effect, an approximate expression for the maximum value of the apparent velocity due to swinging is given by (see Fig. 6)

$$\langle V_{err} \rangle_{max} = \frac{2h \tan(\theta_{max})}{\Delta t} \tag{2}$$

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interval between images, If this interval is near an integral multiple of the swing period, then the difference in the angle of deflection would be minimized. Tests on a prototype of the Martian balloon have indicated that the period of the swinging motion is on the order of 30-35 seconds. Thus, choosing a time separation of 30 or 60 seconds may reduce the effect of this error on the estimated wind velocity.

Table 1
Maximum velocities and errors due to camera swing*

Height, km	V_{max}, ins-l	Velocity error, ins-l			
		θ_{max} = .25°	θ_{max} = .50°	θ_{max} =1 .O°	θ_{max} =2.0°
0.5	5.3	0.15	0.29	0.58	1.16
1.0	10.7	0.29	0.58	1.16	2.33
1.5	16.0	0.44	0.87	1.75	3.49
2.0	21.3	0.58	1.16	2,33	4,66
2.5	26.7	0.73	1.45	2.91	5.82
3.0	32.0	0.87	1.75	3.49	6.98
3.5	37.3	1.02	2.04	4.07	8.15
4.0	42.7	1.16	2.33	4.65	9.31

● Assumes At= 30 see, f = 6.0 mm, η_ρ = 15.0 μm, **Ap = 128 pixels in Eq. (1) and (2).**

A larger swing amplitude of 1-2 deg. is expected during the ascent of the balloon to its cruising altitude of 3-4 km. As is evident from l'able 1, a swing amplitude of this magnitude would make accurate estimation of velocities very difficult without some means of correcting for the swinging motion. For this reason, this paper will only consider the problem of estimating the balloon velocity during the "cruise" phase of the trajectory where the. swinging motion has a smaller amplitude and the balloon altitude remains relatively constant.

Trajectory simulations

in order to determine the expected accuracy of the estimated balloon velocity during cruise phase, simulated balloon trajectories provided to us by a group at the NASA Ames I.abet-story [11] have been used to generate a number of sequences of simulated images of the Martian surface. The balloon trajectories were the result of a study that used a global circulation mode] of the Martian atmosphere based upon a similar model of the Earth's atmosphere[12]. The purpose of this study was to estimate the distance and direction of balloon motion at different locations on Mars at different times of the Martian year. Figure 7 shows a typical balloon height and horizontal velocity profile for one of the trajectory simulations.

Estimation of balloon velocity

A simple four state Kalman filter/sJnoother was used to process the image shifts computed from registration of pairs of simulated images and balloon altitude measure-

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will be no better than 0.5 pixels in each direction. The expected accuracy of the altimeter is 2.0 m.

When generating images from the simulated topography, the balloon camera was modeled as a simple plane pendulum with a period of **32.5** seconds and an amplitude of 0.25 deg. The horizontal and vertical motions of the balloon were taken from the simulated trajectories described above. At intermediate points, where the simulated trajectory does not provide a velocity or height, the velocity and height were modeled by first order Markov random processes. It was also assumed that there would be a residual rotational offset between successive images that was modeled as a mean zero Gaussian process with a standard deviation of 0.5 deg. All images were 256 by 256 pixels and the separation between images was fixed at 30 seconds.

Figure 8 shows the results from a typical simulation. Each point represents the estimated velocity and uncertainty as determined from processing all of the measurements through the filter/snloother. Also shown in this figure are the "true" or modeled velocities that were used to generate the simulated measurements. The simulations were carried out for 2 cases with maximum camera swing amplitudes of 0.25 and].0 deg. In each case the formal errors of the smoothed velocities are on the order of 0.2-0.3 ms^{-1}. However, it is evident that the larger swing amplitude produces a much less accurate estimate of the true velocity,

SUMMARY

Tracking the motion of a wind driven Martian balloon will provide important information on the dynamics of the Martian atmosphere. A technique using onboard processing of balloon camera images has been tested with simulated images of the Martian surface. Within the confines of this simulation, it appears that it should be possible to obtain useful estimates of the velocity of the balloon during its cruise. phase. The problem of estimating the velocity of the balloon during the ascent and descent phases of the flight is a more difficult problem that may require more sophisticated image processing algorithms or the addition of other sensors to the balloon payload. investigations of these possibilities are now underway.

ACKNOWLEDGMENT

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