Mars Lander Position Estimation in the Presence of Ephemeris Biases

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THE Viking missions are designed to conduct scientific surveillance of the planet Mars through the use of two orbiting spacecraft (orbiters) and two spacecraft landed on the Martian surface (landers). Accurate knowledge of the location of the landers and the dynamical state of the orbiters will be required to optimize the performance of various mission phases and to maximize the scientific information acquired. Information on these spacecraft states will be obtained through the application of statistical estimation techniques to Earth-based radio range and Doppler tracking data.

It is known[1,2] that in order to obtain an acceptably accurate estimate of the lander location, from the limited amount of data that will be available during the early phases of the mission, it is necessary to utilize range data in conjunction with Doppler data. For example, when data noise (10^{-3} m/sec) is the only error source, and lander position and Mars pole location are the only estimated parameters, lander position uncertainties of 25 km (1σ) can be expected using only lander Doppler data. The addition of a single range point (15 m uncertainty) reduces the uncertainty in location to well below 1 km. However, with a more realistic solution set (containing certain Mars ephemeris parameters) and a realistic set of model errors, the lander position error is about 13 km. The full strength of the range data cannot be utilized by the filter because of the high linear correlation between the estimated planetary ephemeris components and lander position components. Post-flight scientific analysis of long data arcs with large solution sets may yield accuracies of the order of several kilometers. However, such solution techniques may not be practical for real-time mission operations.

Based on the above considerations, a dual spacecraft tracking (DUST) technique[2] is presented for substantially improving the estimation of the lander location through compensation of errors in the Martian ephemeris before the lander data are processed. The data analysis technique utilizes nearly simultaneous range and Doppler data from a lander and an orbiter in the following manner: 1) estimate the orbit of the orbiting spacecraft from its Doppler tracking data only (this process is not substantially corrupted by ephemeris errors); 2) using the resulting estimate of the orbit, predict the orbiter range data (this prediction should differ from the observed data by a nearly constant value, which is the ephemeris bias); 3) assume that the range bias is the average difference between the predicted and observed orbiter range data; 4) adjust the lander range data by the assumed bias; and 5) use the lander Doppler data and the adjusted range data simultaneously to estimate the lander location. The efficacy of this technique was checked by simulation and covariance analysis.

The covariance analysis of the lander estimation process was conducted by application of the weighted least squares estimator in the same manner as in Ref. 2. Model error covariances were also similar except for Mars ephemeris position and velocity errors, which were taken as 5, 10, 50 km and 0.5, 1.0, and 5.0×10^{-6} km/sec in the radial, downtrack, and crosstrack directions. The lander tracking schedule was assumed to consist of approximately 30 min of Doppler per day for 5 days with one independent range point on the third day. Approximately one orbit of Doppler and range data from the orbiter are assumed to be available also on the third day. Satellite orbit geometry and lander location are consistent with a Viking landing on July 4, 1976, in the northern hemisphere of Mars.

Table 1 Summary of covariance analysis and simulation results

	Standard deviations from lander range and doppler data only		Standard deviations from simultaneous orbiter and lander range and range-rate		Differences from simulation of DUST technique	
	NME	WME	NME	WME	NME	WME
Lander location						
r-spin, km	0.6	0.7	0.6	0.7	0.5	0.5
longitude, rad $\times 10^4$	2.1	2.2	2.1	2.2	0.5	0.5
Z, km	12.7	12.7	1.6	1.9	−1.6	−1.6
Mars pole location						
P, rad $\times 10^4$	3.2	3.3	3.2	3.3	3.2	3.2
Q, rad $\times 10^4$	6.1	6.4	6.2	6.4	−2.7	−2.7
Ephemeris position						
radial, km	4.9	4.9	0.4	0.6		
downtrack, km	6.4	6.4	6.1	6.4		
Ephemeris velocity						
radial, m/sec	4.8	4.8	4.7	4.8		
Orbiter state						
RMS position	...	...	7.9	18.6		
RMS velocity	...	...	1.4	3.4		

Table 1 gives the results of the covariance and simulation studies. The first two data columns are the standard deviations for the solution set of lander related parameters when only lander range and Doppler data are processed. This estimation set was chosen on the following basis. The contribution to the lander position uncertainty was calculated for each of the other parameters in the problem considered as an error source. If a parameter contributed an uncertainty of approximately 1 km or more to the lander position, that parameter was included in the final estimation list. The NME (No Model Errors) column represents the standard deviations when the only error source is data noise. Parameters which contribute to the WME (With Model Errors) column include errors in the tracking station locations, unestimated ephemeris components, and the rotation rate of Mars. Because of the manner of defining the solution set, model errors have little effect on the covariances. However, for this case the linear correlation coefficient between the radial ephemeris position component and the lander Z components is nearly unity. Since the a priori uncertainty on the ephemeris radial position was 5 km, it is seen that this high correlation is limiting the strength of the range data to improve the ephemeris as well as the lander location.

As a basis for comparison, a covariance analysis was performed assuming that all available data from the orbiter and lander are processed simultaneously to estimate the lander related parameters and the orbiter state. The uncertainty in the gravity field is now considered as an additional model error. The main effect of the simultaneous processing of data is to reduce the linear correlation coefficient between lander Z and ephemeris radial components to approximately 0.3, with the corresponding reduction in the standard deviations as shown in Table 1. The orbiter state is corrupted significantly by the gravity field errors. However, this does not feed into the lander location estimate, because gravity field errors primarily produce a biased estimate of the orientation of the orbit around the line-of-sight,[2] and errors in orientation about the line-of-sight do not bias the all important range data.

The last two columns of Table 1 show the results of a simulation wherein pseudo range and Doppler data were

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generated and random noise was added to the data. The numbers are the actual differences between the true and estimated lander position components and Mars pole location parameters after performing the five steps of the DUST technique. The first column corresponds to the noise only case and the second column corresponds to the case where values for errors in the error model parameters were selected at random. The errors are comparable to the covariance analysis and demonstrate the feasibility, practicability, and strength of the DUST technique to reduce the lander position error by almost an order of magnitude below the results obtained from normal data processing and without the sophistication required by simultaneous spacecraft estimation.

References

[1] Russell, R. K., "The Use of Orbiter Range Data in Determining Lander Position," NASA TM 391-203, June 1971, Jet Propulsion Lab., Pasadena, Calif.

[2] Tolson, R. H., Blackshear, W. T., and Anderson, S. G., "Orbit and Position Determination for Mars Orbiters and Landers," *Journal of Spacecraft and Rockets*, Vol. 7, No. 9, Sept. 1970, pp. 1095–1100.

Base Drag Calculations in Supersonic Turbulent Axisymmetric Flows

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Introduction

THE objective of this work is to calculate the base drag of axisymmetric bodies with turbulent boundary layers in supersonic flows, including the effect of base bleed. In this flight regime, the base drag is a major component of the total drag of re-entry vehicles, projectiles, and some rockets.

The method of solution is based on the "flow model" approach, first used by Chapman and by Korst for planar flows, and by Zumwalt and by Mueller for axisymmetric flows (see Ref. 1 for historical development). In previous work, the cone-tail flow model has been used to successfully calculate the base pressure on slender bodies[1] (cylinder flow), including the effect of boat-tails and flares,[2] and on plug nozzles and expansion-deflection nozzles.[3,4] These original articles[1-4] may be consulted for details of the original analysis.

Modifications to Original Analysis

The earlier analysis[1-4] has been modified in two aspects regarding an iteration procedure and the choice of the wake radius ratio.

The analysis necessitates that the dimensionless base bleed parameter G_d' be normalized by the values of density and velocity, ρ_{2a} and U_{2a}, at the edge of the separated shear layer; thus, $G_d' = \dot{m}/\rho_{2a} U_{2a} A_b$, where $\dot{m}$ = dimensional base bleed rate and A_b = base area. This parameter is related to that normalized by the known freestream conditions, $G_d = \dot{m}/\rho_\infty U_\infty A_b$. However, the relation between G_d and G_d' depends on the angle of the dividing streamline, θ_{12}, and is therefore part of the solution (except that $G_d = 0$ implies $G_d' = 0$). Closure of the system is provided by the recompression condition on pressure.[1-4] In previous work, the solution of the nonlinear integral equation for the velocity ratio φ_{j3} was obtained by specifying zero base bleed ($G_d' = 0$) and iterating on θ_{12} until the recompression condition was met. In the present work, the calculation procedure has been changed so that the recompression condition is enforced and the resulting G_d' is solved. Thus, each iteration value of θ_{12} gives a base flow solution for some value of G_d'; we then iterate on θ_{12} until the desired G_d is reached. For $G_d = 0$, the convergence properties are improved. For $G_d \neq 0$, an entire nested iteration loop is avoided, since it is not necessary to iterate on θ_{12} until the recompression condition is met for a guessed G_d' and then iterate again until the desired G_d = function (G_d', θ_{12}) is met. The new procedure requires evaluation of the "inverse" error function, accomplished by Newton-Raphson iteration.

In previous work,[1-4] the wake radius ratio r_w/r_b had to be specified. The equation used was based on experimental data compiled by Chapman[5] from Schlieren photographs of the wakes of slender bodies, approximating the upstream conditions for cylindrical flow. It was known from numerical tests that the solution was fairly insensitive to r_w/r_b, but that the experimental value would almost certainly be dependent on the forebody solution for short bodies. Further, r_w/r_b was shown experimentally[4] to change with G_d, and would likely depend on the specific heat ratio γ. In the present work, we have modified the flow model to include a criteria for r_w/r_b; that value of r_w/r_b is selected which maximizes the base pressure. The results for cylinder flow using this criterion are compared to previous calculations[1] and the experimental data compilation[1] in Fig. 1. The results are in good agreement with the previous method and both are well within the scatter of the experimental data. Although the new criterion significantly increases the computer time used (the particular method used to search for max P_b requires at least 5 solutions at different values of r_w/r_b), the advantage is that only one empirical constant remains in the theory (the jet spreading parameter, σ, related to eddy viscosity).

New Applications

The base pressure P_b and base drag C_{Db} can now be solved for cylinders, sharp cones, blunt cones, and other axisymmetric bodies, including the effects of small base bleed, in the computer program BASE8. The cylinder calculation of BASE8 is that of previous work,[1,2] as previously modified.

For sharp cones, the Taylor-Macoll sharp cone theory is used for the forebody solution. The resulting two-point nonlinear boundary value problem is solved numerically as a subprogram block in BASE8. This radially-similar solution is then converted to data along the first characteristic line from the shoulder by numerical quadrature. The flow along the cone-tail DSL is then computed, for each iterated wake angle θ_{12}, by an axisymmetric homentropic method-of-characteristics (MOC) subprogram block.

In order to calculate P_b for blunt cones and other axisymmetric bodies, the forebody flowfield is calculated in a separate program. Blunt body solutions (such as a spherical nose) are obtained with the inverse method of the NASA Ames program[6] for $M_\infty \simeq 4$ or higher, or with the time-dependent Moretti program[7] for lower M_∞. The remainder of the forebody calculation is done by MOC in the NASA Ames program.[6] The punched-card output at the base is then used to start a nonhomentropic MOC calculation in BASE8.

The BASE8 MOC calculation does not allow for the development of embedded shocks. If a lip shock starts to

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