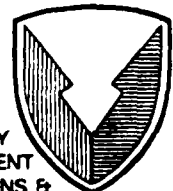AD

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DETERMINING THRUST OR DRAG OF A ROCKET-ASSISTED PROJECTILE FROM DOPPLER TRAJECTORY DATA

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An analysis and associated computational technique were developed to measure rocket thrust using Doppler radar velocity trajectory data from rocket-assisted projectile firings. This technique was inserted into the ARDC standard six-degree-of-freedom flight simulation program, TRAJ5. During data reduction, the actual Doppler velocity from radar data is compared to the value predicted by the simulation. If they disagree, the thrust is adjusted until agreement occurs. The technique automatically determines rocket motor ignition and burnout

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20. ABSTRACT (cont)

times. The estimate of the specific impulse is also corrected. This method can also be used to estimate corrections to the drag coefficient of a projectile.

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INTRODUCTION

A major effort in the past several years at ARDC has been the development of extended range projectiles using rocket assist or base burning techniques. Measurement of the free-flight thrust of the rocket motors in projectiles is even more difficult and expensive than such measurements for missiles, since the launch environment, spin, ambient temperature and pressure, and the flow of air over the projectile all affect the thrust. Therefore, a measurement technique for use in free flight is required. Current experimental techniques obtain positional or Doppler radar data of a flight trajectory from which projectile thrust must be reduced. The data reduction method previously available employs a two-degree-of-freedom flight simulation of a point mass with drag. It has been in use at ARDC for an extended period to extract thrust histories from Doppler radar measurements made during the flight of rocket-assisted munitions (ref 1). It approximates the non-collinearity of the projectile velocity and radar beam, and numerically differentiates the geometrically corrected, measured Doppler velocity. It then uses Newton's equations-of-motion to account for the difference between measured and simulated Doppler accelerations as being due to the thrust. This method has been somewhat successful with rocket-assisted projectiles and artillery rockets, although its output of thrust-time histories was often quite noisy.

When experimental Doppler data for base-burning projectiles (whose thrust levels are very low and whose ignition times are somewhat uncertain) became available, the technique sometimes failed to converge to any solution. Therefore, a better method was sought which would overcome the difficulties inherent in this problem. The new technique subsequently developed was incorporated into a modified version of the ARDC standard six-degree-of-freedom flight simulation TRAJ5 (ref 2). Within this new method of data reduction, the actual measured Doppler velocity from radar data is compared to the value predicted by the new simulation, THRAD. If there is disagreement, the thrust is adjusted until the predicted Doppler velocity agrees with the measured Doppler. In addition, THRAD automatically determines rocket motor ignition and burnout and corrects a user supplied estimate of the specific impulse of the motor.

DISCUSSION

Analysis

Given a method for solution of a large algebraic/transcendental vector equation with a set of outputs or dependent variables, and given a data set representing the time history of one of the dependent variables as measured experimentally, a time history can be found of a single parameter of the equation so that the difference between the computed and measured dependent variable is reduced to a given value of less. A solution of this problem had been implemented at ARDC. The equation was a two-degree-of-freedom, point mass with drag, flight trajectory simulation; the parameter was the thrust, and the dependent variable

was the rate of change of the slant range. The data used was the Doppler radar measurement. The technique used the numerical derivative of the Doppler radar data solving Newton's equation of motion algebraically at each point. This was done in time for the thrust required to make the error in the rate of the change of slant range zero after one numerical integration step. The method was limited because it had no wind model, did not allow for the Doppler radar position to be out of the plane of the line of fire, and could not predict the drift of the projectile. Moreover, the output results (thrust versus time) were visibly very noisy. Therefore, improvements to the method were desirable.

When the newer base burning projectiles were developed with their very low thrust levels, the radar data sets measured in flight were input to the two-degree-of-freedom data reduction program. It sometimes failed to converge to any solution at all. What was retained after accepting the need for a new technique was the determination to force convergence at each point in the flight rather than force a minimum squared deviation over the flight or some other "distributed" criterion.

The first and most obvious difficulty is the noise and digitization error in the recorded Doppler radar data. To reduce the effect of this noise, a digital least squares cubic spline filter algorithm, "ICSVKU", from IMSL (International Mathematical and Statistical Library) was included within the source code of the program to smooth and interpolate the Doppler radar data (ref 3).

The next difficulty with the previous method was the inherently noisy process of differentiating the Doppler data. To solve the noise problem, it was necessary to approach the solution from another direction. Newton's method of solution of the following algebraic problem was performed for each integration time step:

1. A parameter (thrust) is chosen of the differential equation,

2. A value for the parameter is selected and the differential equations of flight are integrated (a linear process),

3. An output (a locally linear process) is generated which can be compared directly with the smoothed Doppler data, and

4. The value of the parameter (thrust) is adjusted as required to reduce the difference between the generated output and the smoothed Doppler data.

This method exploits the numerically generated gradient of calculated Doppler velocity (at the correct geometry, i.e., radar out of the plane of fire and the trajectory out of this plane due to "drift") with respect to the parameter (thrust) only to estimate the correction in the parameter. The effectiveness of the result is tested by integration. If this does not produce a fully converged solution, it is iterated and used to generate a new and better value of the gradient.

Differentiation by numerical means is still being used, which is inescapable for fast convergence. However, it is not noisy Doppler data that is being

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differentiated, but the results of a numerical integration of very smooth aero-
dynamic data, and the integration itself is an additional smoothing process.
Further, the differentiation process does not produce the output; it merely is
used to estimate the place where the solution is found.

The possibility was considered of even this better process producing
unacceptable results (lack of convergence) and a fall back option was planned.
If an initial estimate of thrust did not produce an acceptable result, a marching
technique would be employed to generate a value of thrust whose error was of
opposite sign from the initial estimate. The last value of thrust and its asso-
ciated calculated Doppler velocity, along with the previous pair, form a
"straddle" of the root of the algebraic problem. An intermediate value can be
selected and used to substitute for either the right or left member of the
straddle, as appropriate. This process, when iterated, always converges to a
solution as long as there is only one root within the original straddle, without
recourse to differentiation at all. Its disadvantage is that it has high compu-
tational overhead and converges slowly. If there are an even number of roots in
the straddle at any time, the convergence will fail.

Numerical experiments with actual experimental free-flight data at high
thrust, and at the more difficult low thrust values of a base burning projectile,
have never failed to converge to a solution. Therefore, the "straddle" method
has not yet been implemented.

Consideration was given to adding additional "damping" to the solution by
limiting either the amount or rate of change of estimated thrust. Numerical
experiments early in the development showed significant effectiveness at the cost
of creating errors at the beginning and end of the burning. The need for such
additional "damping" was prevented by using the cubic spline-smoothing filter for
the input data which was effective in removing the noise. The output now
appears, for real cases of interest, to be adequately smooth and accurate. The
accuracy is good enough that the algorithm can be used to estimate drag error in
the aerodynamic data, compensate for it, then detect the ignition time. The
algorithm is presented in the next section in a generalized format that can be
adapted to reduce any parameter from the Doppler velocity data that can be
linearly related (at least approximately over a limited range of values) to the
Doppler radar velocity. Thrust and drag are examples of such parameters.

ALGORITHM FOR THRUST REDUCTION

The algorithm presented here is a general iterative technique that can be
used to reduce any parameter P (such as drag form factor or thrust) that is at
least approximately linearly related to the Doppler velocity over some domain.
In each integration time step, a sequence of estimates of the parameter P is
made, each one improving on the previous estimate made in that time step. With
each improved estimate of the thrust, the integration time step is iterated until
the estimate of the parameter P yields a calculated Doppler velocity that agrees

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with actual Doppler velocity. In general, this sequence of approximations to the parameter P can be represented by

$$P_{r,n} = P_{r-1,n} + \Delta P_{r,n} \tag{1}$$

where

$P_{r,n}$ is the rth estimate of the parameter P for the nth integration time step,

$P_{r-1,n}$ is the previous parameter estimate, and

$\Delta P_{r,n}$ is the rth estimate for the parameter correction in the nth integration time step.

At the beginning of each integration time step, the parameter P determined at the end of the previous integration time step is used as the first estimate. This would be correct if the parameter were of constant effectiveness and, in any case, should be a reasonable first guess. Thus

$$P_{1,n} = P_{n-1} \tag{2}$$

and

$$\Delta P_{1,n} = 0 \tag{3}$$

where

P_{n-1} is the final parameter P estimate from the previous integration time step. At the beginning of a thrusting stage, it is taken to be zero, since there is no previous thrusting time step. At the beginning of a drag reduction stage, it is taken to be 1.

The difference between the actual and calculated Doppler velocities can be expressed by the following expression

$$\Delta D_{r,n} = D_{r,n} - D_{act} \tag{4}$$

where

$D_{r,n}$ is the Doppler velocity calculated from the results of doing the nth integration time step with the parameter $P_{r,n}$, and

D_{act} is the actual Doppler velocity from radar, as smoothed and interpolated.

Whenever this difference is sufficiently small (less than the tolerance), no parameter P correction is needed and the computer simulation proceeds to the next integration time step.

If the difference between the actual and the simulated Doppler velocities is greater than that specified by the tolerance, the projectile parameter must be adjusted. The development of an estimation table for this purpose is started at the beginning of each integration time step during a data reduction phase. The first point for this table is obtained using the Doppler velocity difference and a zero parameter adjustment. This point in the table merely states that making no adjustment to the parameter P (using the value for P determined in the previous time step) produces the Doppler velocity difference that was obtained upon the initial integration trial on the particular integration time step. One more point must be obtained before a slope can be calculated to approximate the partial derivative with respect to the Doppler velocity of the parameter correction. Therefore, an intelligent initial estimate of the parameter correction required to reduce the Doppler velocity difference to zero must be made without recourse to the incomplete table. If the parameter P is the thrust T, then this is done most appropriately by using Newton's law of motion, relating the time rate of change of momentum to the force producing it. In this case (for $r = 1$)

$$T_{1,n} = P_{1,n} = M \Delta D_{1,n} / \Delta t \tag{5}$$

where

   M   is the mass of the projectile, and

   Λ t is the integration time step.

If the parameter P is the drag form factor F, then an appropriate estimate might be

$$F_{1,n} = P_{1,n} = 1 \pm |\varepsilon| \tag{6}$$

where the positive sign is used if ΔD is negative and the negative sign is used when Λ D is positive. A suitable value for $|\varepsilon|$ would be 0.4.

The nth or current integration time step is redone using the above increment to the parameter (thrust or drag form factor). Ideally, the trial integration using the new parameter estimate should reduce the Doppler velocity difference to zero. If this happens, the simulation will advance to the next integration time step.

If convergence has not been achieved, the last parameter increment, Δ P, and the resulting Doppler velocity difference, Δ D, are included as a second point in the estimation table. With two points, the slope can be obtained and used to approximate the partial derivative of the parameter P with respect to the Doppler velocity difference.

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Thus, for all values of r greater than 1, the parameter correction is

$$P_{r,n} = -s \, \Delta \, D_{r-1,n} + P_{r-1,n} \qquad (7)$$

where

s is the slope (partial derivative approximation) and is given by

$$s = \left[P_{r-1,n} - P_{r-2,n} \right] / \left[\Delta \, D_{r-1,n} - \Delta \, D_{r-2,n} \right] \qquad (8)$$

The subscripted expressions in equation 8 are the points saved in the estimation table. At each step, the latest thrust increment and Doppler velocity difference provide a new point that replaces the oldest point in the estimation table. Thus, this table contains only the two most recent data points for estimating the needed partial derivative. This procedure is iterated to achieve the required degree of convergence.

Programming Considerations

The entire process was incorporated into a special version of the ARDC standard six-degree-of-freedom flight simulation program, TRAJ5. This version comprises six subroutines. The initialization of the algorithm is accomplished in the subroutine DOPSET. The calculation of the Doppler velocity difference and the adjustments to the thrust or drag form factor are determined in subroutine DOPFIT or DOPFITF, respectively. Subroutine SLIDE is used to provide a 25-point sliding cubic spline fit to the Doppler data to remove the effects of noise and to interpolate the data. SLIDE uses the IMSL routine, ICSVKU, to provide a least squares cubic spline fit using variable knots (ref 3). SLIDE accepts an additional Doppler data point and discards one point whenever necessary to interpolate around the midpoint of a set of 25 points. This minimizes sensitivity to the end points. Subroutine THROUT provides a summary of input and results.

Communication among the various Doppler subroutines except ICSVKU is accomplished through the labeled common blocks DOPNAM and DOPL to minimize the execution time of the program. ICSVKU was left as published (ref 3), with a long argument list for compatibility with later releases of IMSL.

TESTING

The first tests were performed with simulated noiseless input data. The simulated Doppler velocity input data was generated using THRAD5 to model a

rocket-assisted projectile with a specific impulse of 240 lb-sec/lb and the following thrust table:

Table 1. Thrust profile

Time (sec)	Thrust (lb)
8.150	0
8.250	930
8.500	1020
8.650	1020
9.000	655
9.650	355
10.150	55
11.360	30

The artificial noiseless Doppler data was generated by TRAJ5 and subsequently used as input to THRAD to see how close this technique could come to reproducing the original thrust table. In particular, the thrust has the constant value 1020 pounds in the time interval between 8.50 and 8.65 seconds. The thrust reduction in this plateau is interesting because this is the region where the reduction should perform best. The correct value for the specific impulse was used in the first trial together with two other trial values, one of which was in error by an order of magnitude. This test shows what the sensitivity of the thrust reduction was to errors in the specific impulse, and how accurately THRAD would estimate a corrected value for the specific impulse. The results are given in table 2.

Table 2. Test results on thrust plateau

Trial specific impulse	Reduced specific impulse	Thrust (lb)	Percent error		
			Trial S.I.	Reduced S.I.	Thrust
240	240.1	1020.07	0.0	0.0	0.0
190	239.4	1017	-20.8	-0.3	-0.3
20	213	905	-91.7	-11.0	-11.0

These results indicated that this technique is robust. Examination of the last line of the above table shows that convergence is rapid, even with a trial specific impulse that is in error by more than an order of magnitude. One iteration produces nearly an order of magnitude improvement in the estimate of the specific impulse, from 91.7% to 11%, with a thrust error of 11%. It is evident from the second line of the above table that an additional iteration using 213 lb-sec/sec as an estimate for the specific impulse would produce convergence. Thus, even with a poor initial value for the specific impulse, this technique can be expected to converge in a very small number of iterations. The first line of the above table shows that the thrust was obtained to five significant figures when an accurate, converged value for the specific impulse is used. Note that this performance depends on precise knowledge of the projectile mass at the beginning and end of the thrusting stage.

Similar performance is found within the other linear segments of the thrust curve. The following table shows the reduced thrust at the midpoint of the various linear segments. The correct specific impulse has been used. The rate of change of the thrust (thrust slope) has been calculated and included in the table for convenience.

Table 3. Reduced thrust at midpoint of linear segments

Time segment (sec-sec)	Midpoint time (sec)	Actual thrust (lb)	Reduced thrust (lb)	Percent error	Thrust slope (lb/sec)
8.15 - 8.25	8.20	465.0	443.5	-4.62	9300
8.25 - 8.50	8.37	973.2	972.4	-0.08	360
8.50 - 8.65	8.58	1020.0	1020.07	<0.01	0
8.65 - 9.00	8.83	832.3	834.7	0.29	-1043
9.00 - 9.65	9.33	502.7	503.8	0.22	-462
9.65 - 10.15	9.90	205.0	206.4	0.68	-600
10.15 - 11.36	10.75	42.6	42.7	0.23	-21

The reduced thrust in the above table tends to slightly lag the actual thrust. That is, the reduced thrust is underestimated when the thrust is increasing and overestimated when the thrust is decreasing. This effect is very evident in the first line of the table where the thrust is rapidly changing (9300 lb per second). Elsewhere in the table, errors are a fraction of a percent.

This noiseless case can be expected to perform with the least accuracy at the corners of the thrust curve, where the derivative is not continuous. The cubic spline fit itself, which is used to filter noise out of the Doppler data,

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introduces error by rounding off these corners. The following table gives some insight into the magnitude of this effect. Again, note that the error lags. Whether the thrust is actually rising or falling, the reduced thrust is always lower or higher, respective'v, than the actual thrust.

Table 4. Test results at slope discontinuities

Time (sec)	Actual thrust (lb)	Reduced thrust (lb)	Percent error
8.25	930.0	902.1	-3.00
8.50	1020.0	1018.9	-0.11
8.65	1020.0	1019.2	-0.07
9.00	655.0	657.9	0.44
9.65	355.0	356.0	0.28

Again, the errors are small except at 8.25 seconds, which is the endpoint of the most rapid rise in the thrust. At this point, the derivative of the thrust changes discontinuously from 9300 lb/sec to 360 lb/sec. Even at such a sharp corner, the error is only 3%. Elsewhere, the error is always less than 0.5%.

CONCLUSIONS

THRAD has been shown to be superior to the previous method of reducing projectile thrusts from experimental Doppler radar velocities. It is possible to obtain more accurate results since THRAD, being a six-degree-of freedom trajectory simulation, can account for out-of-plane effects. THRAD can also correct for meteorological conditions. In addition, the technique described in this report is less noisy and converges where the previous technique fails. It automatically determines thrust ignition and burnout times. Finally, it can be run iteratively to determine the specific impulse when this parameter is not known.

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APPENDIX

PROGRAM USAGE

The basic input pattern for the TRAJ5 six-degree-of-freedom simulation, documented fully in reference 4, is not repeated here. Input record 17 in the original was modified to include the additional variables for THRAD. These are enumerated in the VARIABLE INPUT FORMAT table. Keeping compatibility with the original version of TRAJ5, THRAD requires NTHR to be positive so that PULSEI, the specific impulse, will be read from input record 18. The use of the specific impulse PULSEI is explained in the next paragraph. Compatibility with TRAJ5 also requires that input records 18 through 21 be present when NTHR is positive. However, THRAD will only require PULSEI on these input records when KDOPLR is 1. Any thrust table will be ignored. Instead, the thrust will be extracted by matching the Doppler velocity.

The data reduction is further refined by using the specific impulse, PULSEI, on data input record 18, (usual TRAJ5 format) to determine the change in projectile mass at each time step. Recall that the specific impulse is the ratio of the thrust to the ejected mass. If the final mass of the projectile in the six-degree-of-freedom simulation does not agree with the known final mass of the projectile, the specific impulse can be adjusted proportionately. THRAD does this to yield a revised estimate of the specific impulse, PULSEI, at the end of any thrust reduction stage. The user can then determine whether iteration is desired for better convergence.

If KDOPLR is 2, THRAD will extract a drag form factor, FORMFD, from the Doppler radar velocity data in an analogous manner. This is done in subroutine DOPFITF. In addition to being intrinsically interesting, FORMFD has a practical function in THRAD. When ignition of the rocket motor occurs, the projectile either accelerates or at least has reduced deceleration. THRAD reacts to this by reducing FORMFD significantly. This drop in the value of FORMFD can be used by THRAD to detect ignition Similarly, a drop in the value of THRUST below a threshold (DOPTRIG) can be interpreted by THRAD as thrust extinction.

In practice, this could be done as follows: A non-thrusting stage, N, is followed by a thrusting stage, T. Input record 17 for stage N is blank except for the first eight columns which contain 00220111. Similarly, input data record 17 for stage T is blank except for 02120111. (See the variable input format for input record 17 given in the table below.) Since NTHR is 02 in columns 1 and 2, a two-entry thrust table must appear as explained above. The thrust table is not used, but the specific impulse PULSEI must appear on data input record 18. Since most of record 17 is blank, THRAD will use defaults for EDOPMX, DOPTRIG, and TIMEDP. An unspecified value for DOPTRIG defaults to 0.5 in stage n and to 0.0 in stage T.

In the nonthrusting stage N, KDOPLR = 2 in column 3 tells THRAD to reduce FORMFD from Doppler data. IDOPMX = 2 in column 4 tells THRAD to continue to fly the projectile until FORMFD falls below the default threshold value, DOPTRIG, in two consecutive integration steps. When this occurs, stage N automatically ends, a summary table of FORMFD as a function of Mach number is provided, and the thrusting stage begins. In the next (thrusting) stage T, DOPLR = 1 tells THRAD to derive the thrust from the Doppler data until THRUST falls below the current value of DOPTRIG (default is zero) for IDOPMX consecutive times. When this condition occurs, the thrusting stage ends automatically, and THRAD prints out the reduced total impulse and a table of thrust as a function of time. Since both a

raw thrust table and a least squares cubic spline smoothed thrust table are printed, the total impulse is recalculated from both tables. These can be compared to the reduced total impulse to determine if the tables need scaling.

Table A-1. Variable input format

Recd/col	FMT	Name	Definition
17/1	I2	NTHR	Number of record entries in thrust table. Cannot be zero because of PULSEI.
17/3	I1	KDOPLR	This flag equals 1 for Doppler fitting of thrust. If 2, fit drag form factor FORMFD. If blank or zero, ignore Doppler data.
17/4	I1	IDOPMX	If not zero, stage ends adaptively based on DOPTRIG not being exceeded IDOPMX times consecutively.
17/5	I1	KFORM	Reserved for future use.
17/6	I1	KDPUIN	Doppler input units where 0 is metric and 1 is English.
17/7	I1	KDPUOUT	Units for optional Doppler printout. (Echo of input. See KDPUOUT.)
17/8	I1	KDPPRT	Printout of Doppler data if 1. (See KDPUOUT.)
17/10	F9.0	EDOPMX	Maximum allowable Doppler velocity mismatch.
17/19	F9.0	DOPTRIG	If IDOPMX is positive and KDOPLR = 2, then stage ends when FORMFD falls below DOPTRIG (thrust ignition). If KDOPLR is 1, then end of thrust is detected when THRUST is less than DOPTRIG. (See IDOPMX.)
17/28	F9.0	TIMEDP	Doppler will be ignored until time exceeds TIMEDP.

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