Technical Notes

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Analysis of Radar Returns from a Rocket Plume

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Introduction

RADAR (electromagnetic scattering) data provide a detailed view of the rocket plume (exhaust) flowfield of a Black Brant sounding rocket at 24.2 km. These data allow a quantitative analysis of rocket plume radar dimensions and amplitudes. The rocket nozzle and exhaust flows are calculated using constant pressure, finite rate chemical kinetics, with turbulent diffusion expressed by eddy diffusivity models. The nozzle exit plane flow is isentropically adjusted to ambient pressure to start this diffusion flame calculation. It has been shown by Dash et al.[1] that this flowfield pressure adjustment for rocket plumes is acceptable at altitudes below 25 km. A first-order modified Born scattering calculation is used for estimating the radar observables of the electrical flowfield. It is shown that this technique explains all major aspects of the radar observables and it is expected to perform equally well for other rocket plumes below 20-30 km altitude. This analysis is discussed in detail in Draper and Sperlein.[2]

Discussion

The Doppler shifted radar cross sections (RCS) of "high" altitude (above 100 km) rocket plumes were examined by Draper et al.[3] using a model assuming frozen chemistry, a "frozen" hypersonic turbulence originating in the combustion chamber, and the Booker-Gordon scattering model. In contrast, low-altitude (below 30-40 km) plume flows are characterized by fast chemical processes, large electron-neutral collision frequencies, and intense turbulence generated in shear layers. Excellent rocket plume radar data, described by McIntyre and Lynch,[4] provide a detailed description of the Black Brant RCS values and their Doppler and spatial behavior with altitude. The Black Brant body and plume are reconstructed at 29.3 s after launch and 24.2 km altitude in Fig. 1. The 200-m-long electrical plume observed far exceeds the 2-3 m length of the first Mach cells which accommodate the exhaust to the ambient flow. Hence, most of the flow in which mixing and electron scattering originates is pressure matched and shock free. The rocket nozzle and plume flows were calculated using finite rate chemistry nozzle and plume constant pressure codes, FULLNOZ[5] and LAPP,[6] respectively. The FULLNOZ calculations were carried out by H. S. Pergament,‡ and the LAPP calculations by R. F. Sperlein.

The Black Brant exit nozzle conditions are based on a nozzle area ratio of ~7.8 and a chamber pressure of 4.5×10^6 N/m^2. Inclusion of finite rate chemistry effects has a first-order effect on the initial electron concentration, but a negligible effect on the major species properties. Isentropic expansion of the nozzle conditions to an ambient pressure of 3.02×10^3 N/m^2 provides the LAPP input conditions. Dash et al.,[1] who examine the effect of various starting techniques on plume calculations at altitude, show that at and below 25-km altitude the temperature boosts associated with shock (total pressure) losses are small, significantly less than 10%. This applies even to the isentropic expansion technique used here. This expansion can be replaced by techniques accounting for "global" pressure losses in the exhaust shocks.[1] The Black Brant centerline temperature and electron concentration profiles, for the Ting-Libby[7] and Donaldson-Gray[8] eddy diffusion models, shown in Fig. 2, illustrate that the length of the calculated electrical plume compares well with the measured length of the radar plume of Fig. 1.

The sensitivity of these calculated plume structures to several uncertainties was assessed.[2] The Black Brant motor produces Al_2O_3(s) which is chemically inert and is decoupled from the chemical processes. A study of the radar cross section of the Al_2O_3(s) by Mann and Sperlein[9] shows particle scattering to be negligible. Uncertainties in startline temperatures due to rocket base recirculation[10,11] and afterburning due to chemical rate uncertainties were found to have a relatively small effect on the electrical plume for reasonable ranges of these parameters. The sodium impurities in the Black Brant propellant were subjected to definitive quantitative analysis to specify this dominant source of the plume-free electrons.

The calculated plume RCS profiles, obtained using the PARCS code[12,13] by Sperlein, are shown with the radar data of McIntyre and Lynch in Fig. 3. The centerline electron concentration decay, evident by 150 m in Fig. 2, is compensated by increases in flow diameter so that the reasonably constant profiles in Fig. 3 result. The two calculated RCS profiles provide similar radar cross sections (see Table 1), and compare well with the radar data within the error bounds of the calculations and measurements. The reader should bear in mind the highly absorptive nature of these low-altitude plumes due to the electron neutral collision frequency being much larger than the radar frequency. This effect reduces the Black Brant plume RCS at 24.2 km altitude by ~16 dB. In sum, the overall calculation approach provides a good estimate of all major aspects of the radar observables and can be applied to rocket plumes below 20-30 km altitude.

The agreement among the total RCS values in Table 1 partly results from compensating effects. The predicted axial RCS values at small axial distances are about equal to or small compared to the observed axial RCS values, while this relation is reversed at large axial (>150 m) distances. Quantitatively, this is the same result as that found by Dash et al.[1] with regard to IR "station" axial radiation prediction. They compared predictions obtained using the Donaldson-Gray eddy diffusivity model to those obtained wind two-

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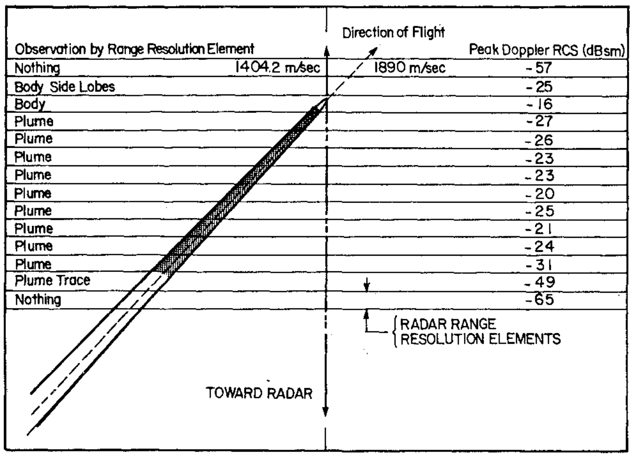

Fig. 1 Black Brant rocket body and radar plume (hatched region) shown in relationship to the radar range resolution elements at 24.2 km altitude. Each radar range element is 15 m in length along the radar line of sight.

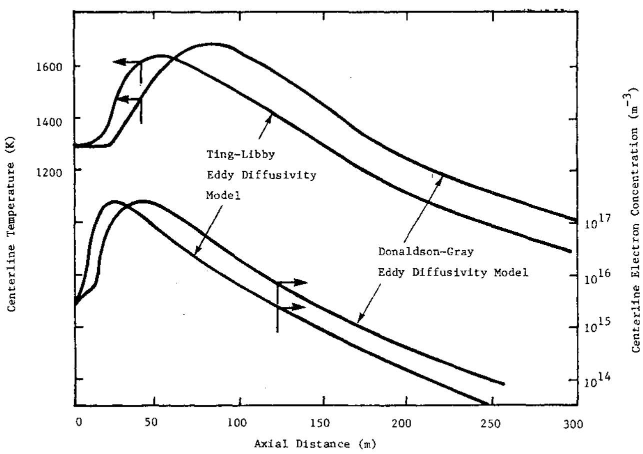

Fig. 2 The plume centerline temperatures and electron concentrations calculated using LAPP and two eddy diffusivity models.[6,7]

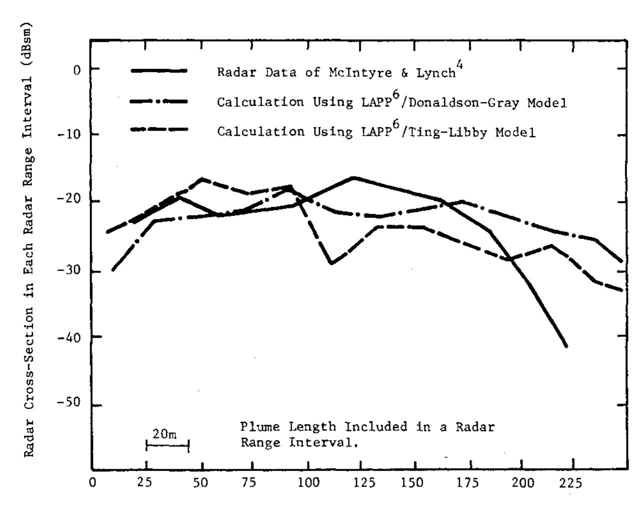

Fig. 3 The observed and calculated radar plumes compared.

equation models (e.g., $K\epsilon 2$ cm^3 turbulence models, see Ref. 1). In both cases, the eddy diffusivity model appears to show the slower mixing at small axial distances and faster mixing at large distances. The net result was that their predictions of total IR signatures, using different turbulence modeling approaches, were in better agreement than might be expected

Table 1 Comparison of RCS values from field data and calculations

RCS source	Total incoherent RCS, dBsm[a]
LAPP calculation[6]	
Donaldson-Gray model[8]	-10.5 ± 5^b
Ting-Libby model[7]	-10.4 ± 5^b
Radar field data	
McIntyre and Lynch[4]	-11.6 ± 2^c

[a]The PARCS[12,13] RCS calculations were carried out at 1.326×10^9 Hz and a viewing angle from nose-on viewing of 138 deg. [b]The ±5 dB spread in uncertainty reflects current judgment that absolute RCS values should be qualified with a factor of 10 uncertainty. [c]While the instantaneous measurement is far less noisy, the ±2 dB covers the continuous scintillation observed in plume total RCS values.

from inspecting the station or axial profiles. The result is that the total signature (IR or RCS) is relatively insensitive to the turbulence model, while spatially resolved data are of greater importance for studying the performance of alternate turbulence calculation methods.

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