Measurement Notes

NOTE 27

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CHARACTERISTICS OF THE FRENCH RUGGIERI ANTI-HAIL ROCKETS USED TO TRIGGER LIGHTNING

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ABSTRACT

Lightning can be triggered by the rapid injection of a grounded wire into regions with strong electric fields beneath a negatively charged thundercloud if the upper tip of the wire moves faster than the drift velocities of corona ions emitted from the wire. Field strengths in excess of 9 kV/m, wire tip velocities in excess of 150 m/sec and wire tip heights in excess of 100 m are required for a high probability of triggering lightning over land.

Measurements of the performance of the French Ruggieri rockets used by Hubert et al. for triggering lightning indicate that these rockets provide impulses of about 640 N s, velocities of about 300 m/sec, peak accelerations of about 30 g with apogees of about 1800 m.

We conclude that lightning may be triggered by use of somewhat smaller rockets, under favorable conditions from mountain peaks.

INTRODUCTION

Brook et al. (1961) suggested that lightning might be triggered by the rapid injection of a grounded wire into the atmosphere beneath thunderclouds. This idea was developed by Morris Newman and John Robb of the Lightning and Transients Research Institute (1965) who triggered lightning repeatedly with wire-trailing rockets fired from a ship at sea. Attempts to trigger lightning from land-based sites over the next decade, however, were generally unsuccessful. There were a few triggerings of lightning over land (Apollo 12, 1969; Standler and Hunyady, New Mexico, 1974, shown in Figure 1) but most attempts resulted in failure. These failures were attributable, in part, to the weaker electric fields that exist beneath thunderclouds over land as a result of the emissions of point discharge ions from the earth under strong electric fields.

Many of the rockets used by various investigators were high-impulse, military rockets that accelerated too rapidly and usually broke the trailing wires before they attained any significant altitude.

FRENCH DEVELOPMENTS

Pierre Hubert and his associates (Fieux, et al., 1975) in the French Commissariat à l'Energie Atomique turned their attention to this problem in the 1970 era. They developed wire dispensing techniques and used a small, plastic anti-hail (paragrêle) rocket, manufactured by Ruggieri, for lightning triggering experiments. As a result of the French effort, it is now possible to trigger lightning over land reliably with a rocket towing a grounded wire

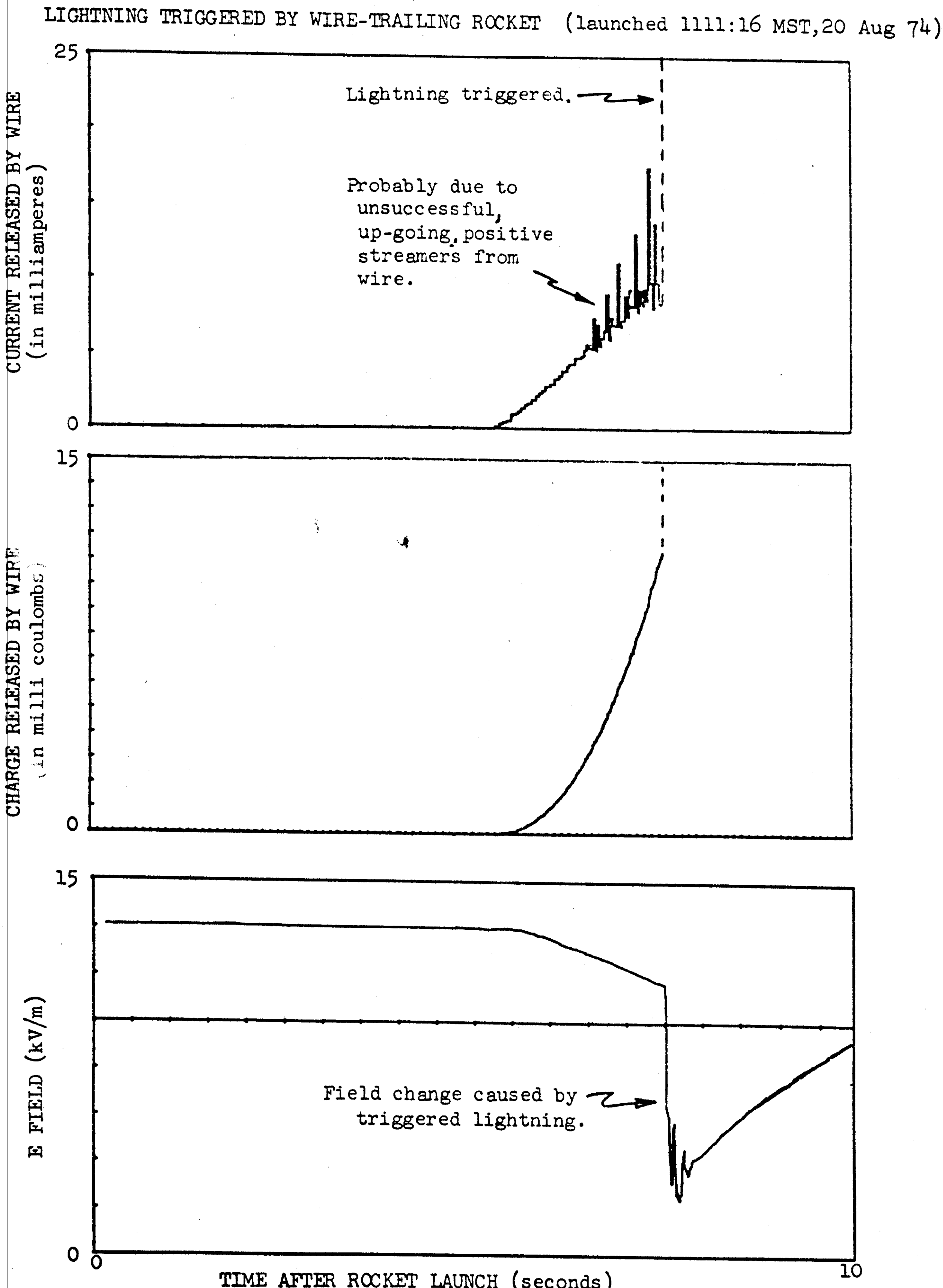

Figure 1. Plots of the electric currents, charge and surface field strengths associated with the launch of a wire-trailing, anti-tank missile that triggered lightning.

whenever a net negative charge is overhead and the electric field strength at the earth's surface is in excess of 9 kV/m. A rapidly moving, wire-trailing rocket, launched under these conditions, produces an upward-going, positive streamer when the rocket reaches a height of the order of 200 m above the local terrain.

To cause a lightning streamer beneath a thundercloud, it appears necessary that the rocket move through the air faster than do the positive ions that are emitted from the upper end of the wire. Otherwise, an accumulation of these ions will reduce the local electric fields below the strength needed for production of a streamer. The estimated drift velocities of positive ions in the electric fields at a height of 200 m are of the order of 100 m/s. Thus, positive ions cannot be accumulated above the French rocket which has an upward velocity in excess of 150 m/s at the altitudes of interest.

1982 FIRING TESTS

In order to obtain some quantitative data on the behavior of the Ruggieri rockets, we made arrangements to fire two of them on the Sandia tracking range, where a laser "theodolite" is available. It is used to track various high speed, airborne vehicles and provides a read-out, once each millisecond, of the slant range and azimuth and elevation angles with a range resolution of about 0.36 m and an angular resolution of 0.003 degree.

On the afternoon of October 14, 1982, we launched and tracked a Ruggieri rocket, without any trailing wires, at a site 1145 m from the tracking laser. This test, identified in the data that follow as "Hail 01" was successful in that the rocket performed well and was tracked until it passed a height of 1000 m above the laser, 4 seconds after the launch. The signal returned to the laser then became too weak to track as a result of the geometric arrangement of the target so that data collection ended. The rocket motor gave thrust for a period of about 1.5 seconds after its launch.

A second Ruggieri rocket was then placed in the launcher and connected to a wire dispensing bobbin with an elastic cord following the French technique. In this technique, a steel wire bridle about 2.5 m long, arranged in a "V", is attached to two adjacent fins of the rocket. A 1 m elastic cord is connected from the vertex of the "V" to the upper end of the wire to be towed by the rocket. The wire used here was steel, covered with a light, 25 micro meter, thick, varnish coating. It had a diameter of 0.20 mm and a mass of 0.275 gm/meter of length. Its breaking strength is of in excess of 80 N so that its static breaking-length is about 30 km under one g.

On insertion of the ignitor, we noted that this rocket had a different perforation in the powder grain of its motor than did the first rocket. This perforation was about 5 cm shorter than the first one so that the ignitor could not be inserted as far as in the first Ruggieri rocket. We examined the motor by removing it from the launcher and turning it so that sunlight illuminated its interior. The perforation appeared to have been constructed so that it terminated smoothly about one half way up the motor.

This construction was a surprise and showed us that we did not have two identical rockets from which we could determine the drag of the towed wire. Since this was the last French rocket available, we proceeded with the test and launched the second rocket. It was tracked for 6.8 seconds before the theodolite lost it at a rocket height of 1150 m. After launch, the rocket motor gave thrust for about 1.7 seconds. The data for this second firing are identified as "Hail 02".

When the test was over, we found that about 185 m of wire were pulled from the dispenser by Hail 02, after which, the elastic cord connecting the top of the wire to the rocket burned through and broke away from the bridle below the rocket. The wire was thereafter unconnected to the rocket so that a fair test of the wire towing effects could not be established for this reason as well as for the differences in burn times and rocket propellant grains. The break occurred about 1.41 seconds after launch, while the motor was still burning and producing an acceleration in excess of 20 g. Sandia plots of displacement, velocity, acceleration and height versus time are shown in Figures 2 through 9. The Sandia data for velocity and acceleration are obtained by sequential differentiation of the position data. No smoothing is initially applied to the differentiated data and the computed raw accelerations show large oscillations. Some of these may be due to intermittent combustion toward the end of the rocket-fuel burn phase but other oscillations appear to be a result of the tracking system behavior. In an attempt to smooth these data, we have digitally filtered the computed position data with a "box car" algorithm.

The oscillations in the computed acceleration have periods of the order of 100 ms. We have, therefore, filtered the position data obtained for each millisecond over 100 ms intervals and listed the

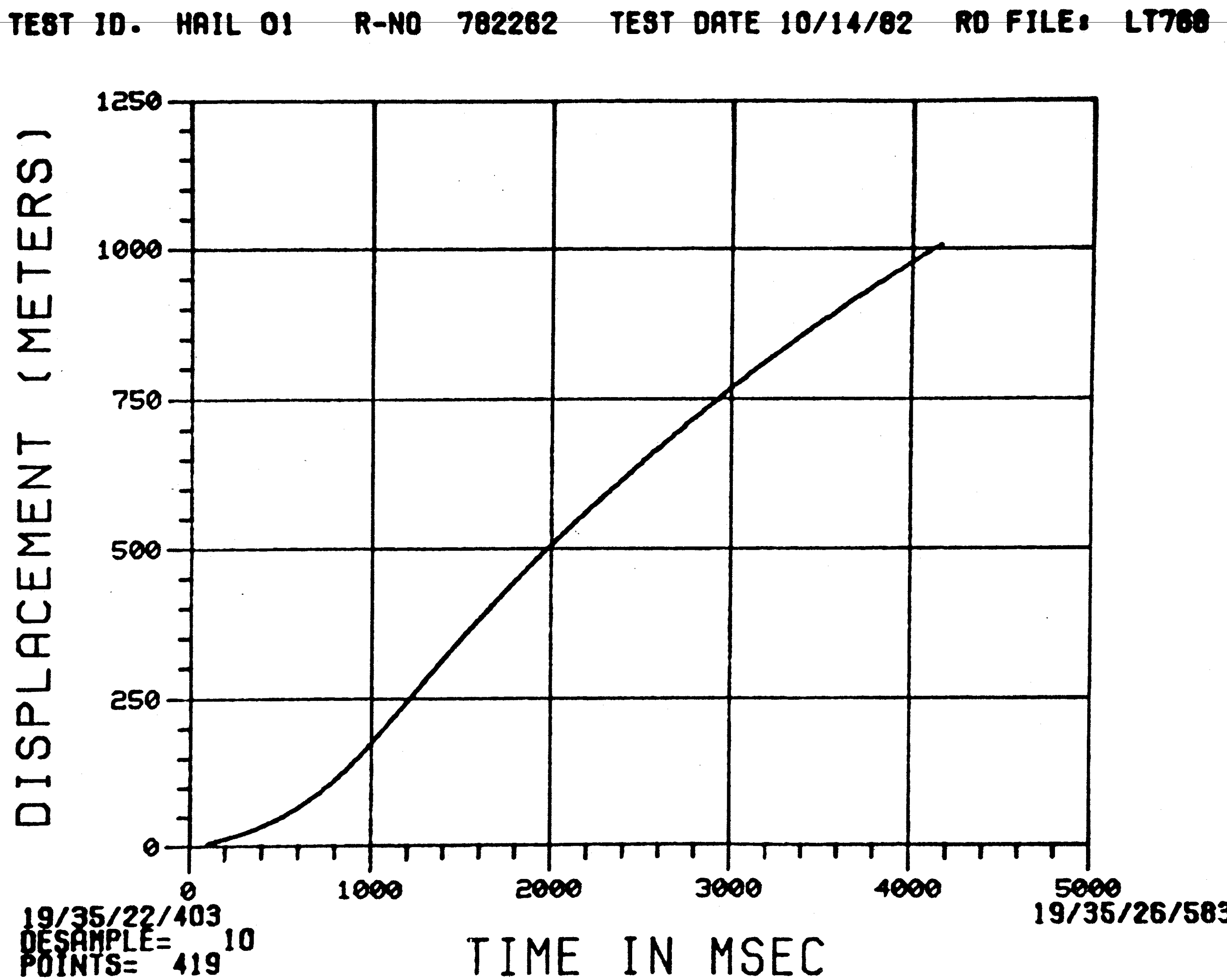

Figure 2. Displacement vs Time for Hail 01
Displacement = $[(x - x_o)^2 + (y - y_o)^2 + (z - z_o)^2]^{1/2}$

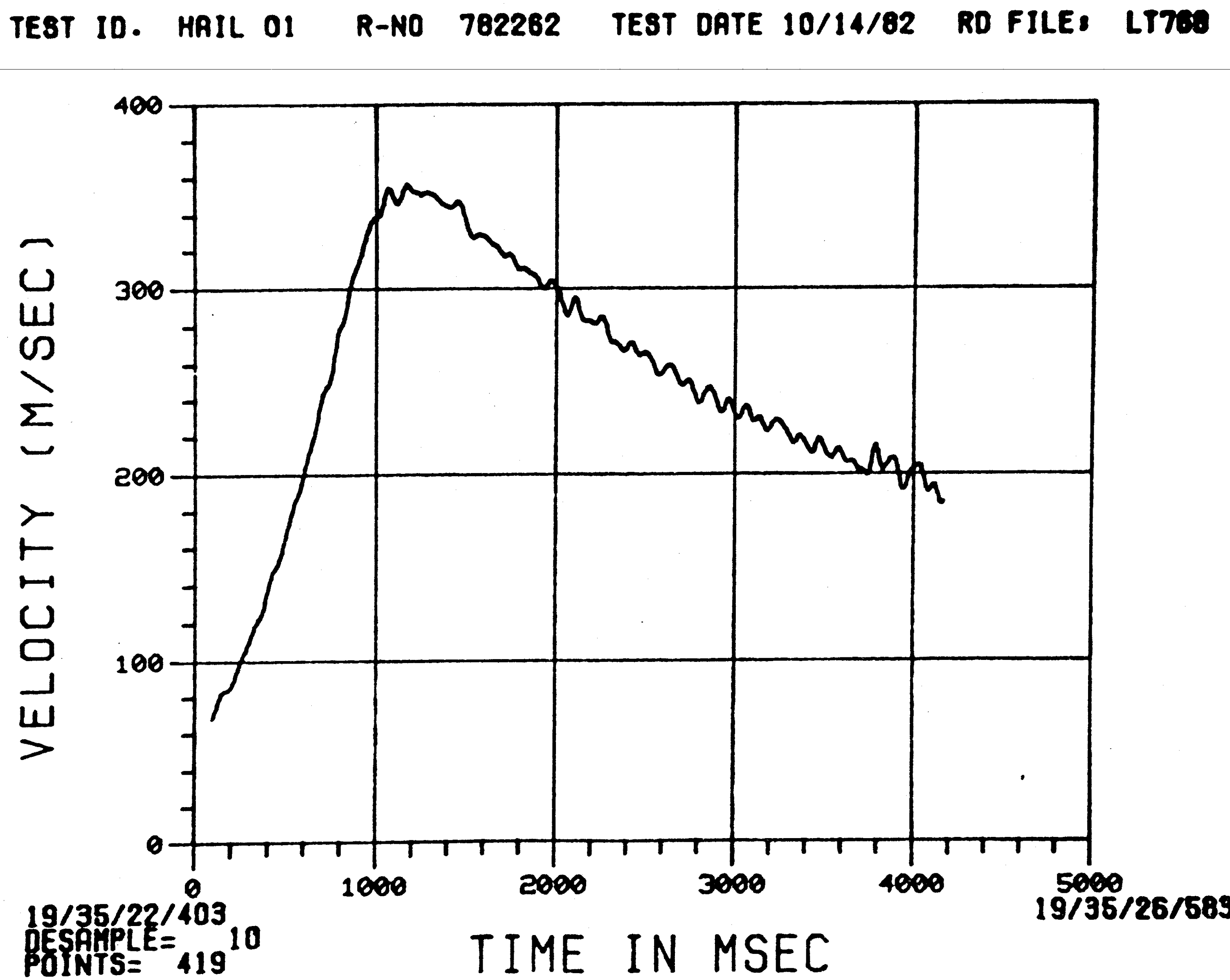

Figure 3. Displacement Velocity vs Time for Hail 01

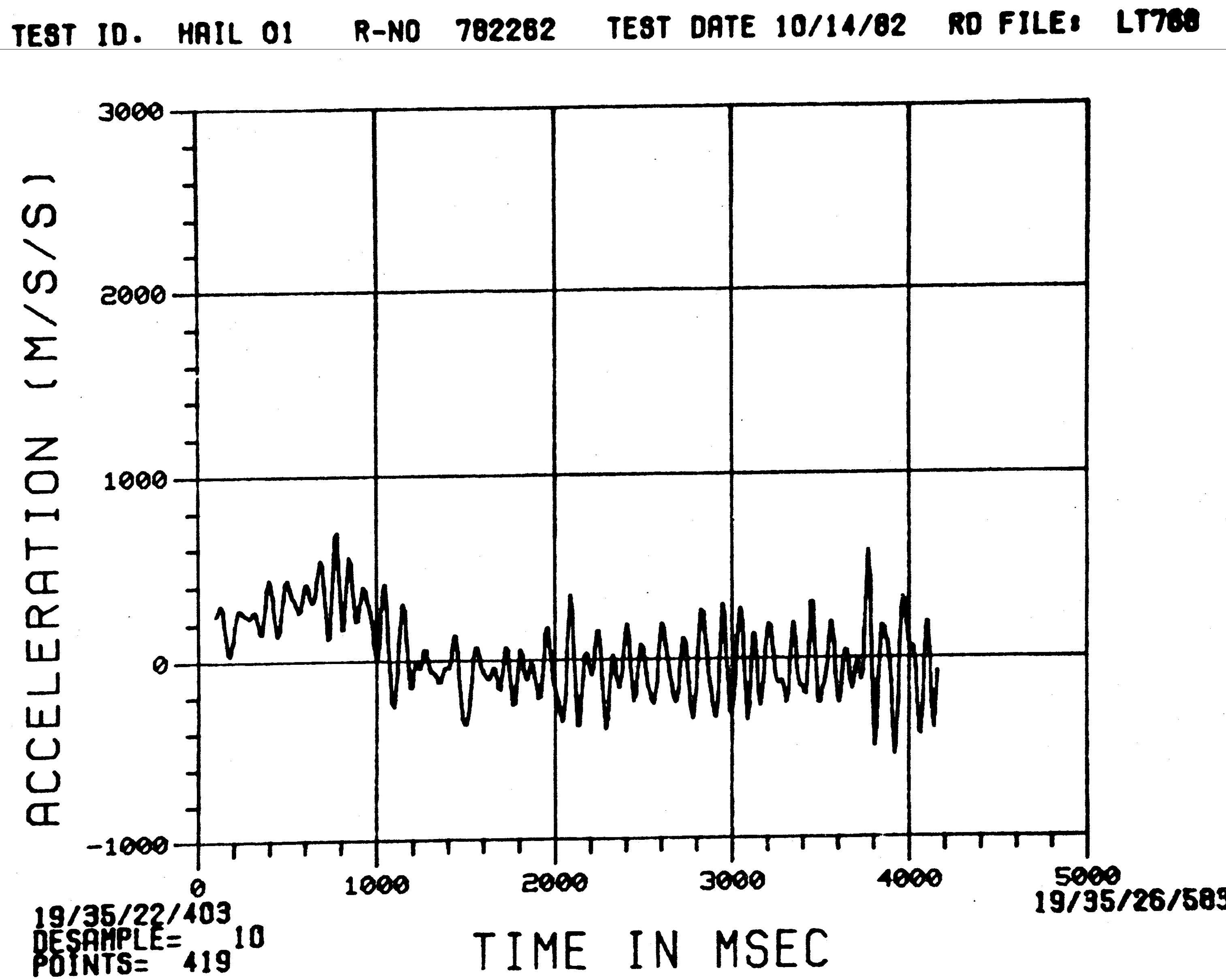

Figure 4. Displacement Acceleration for Hail 01

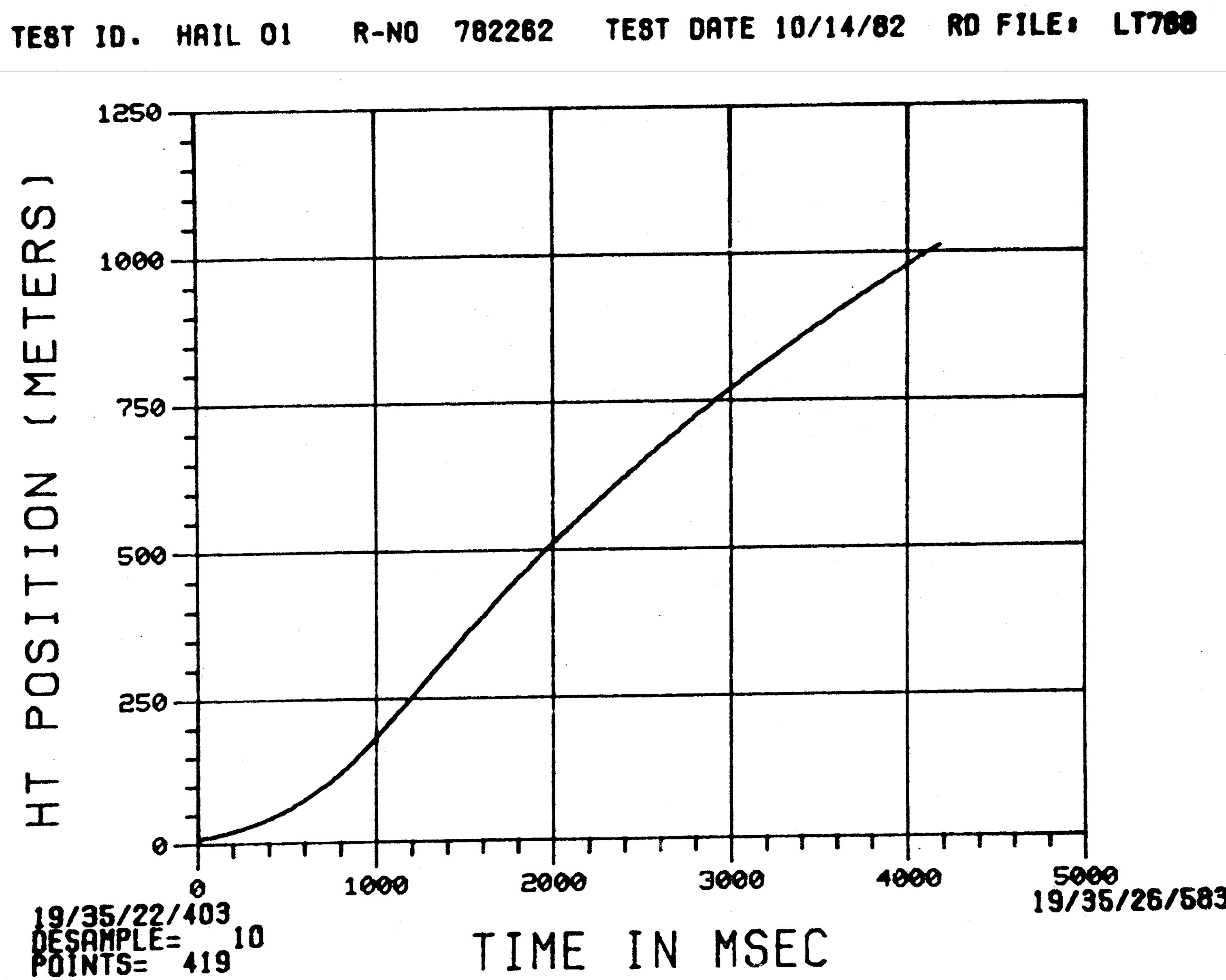

Figure 5. Height vs Time for Hail 01

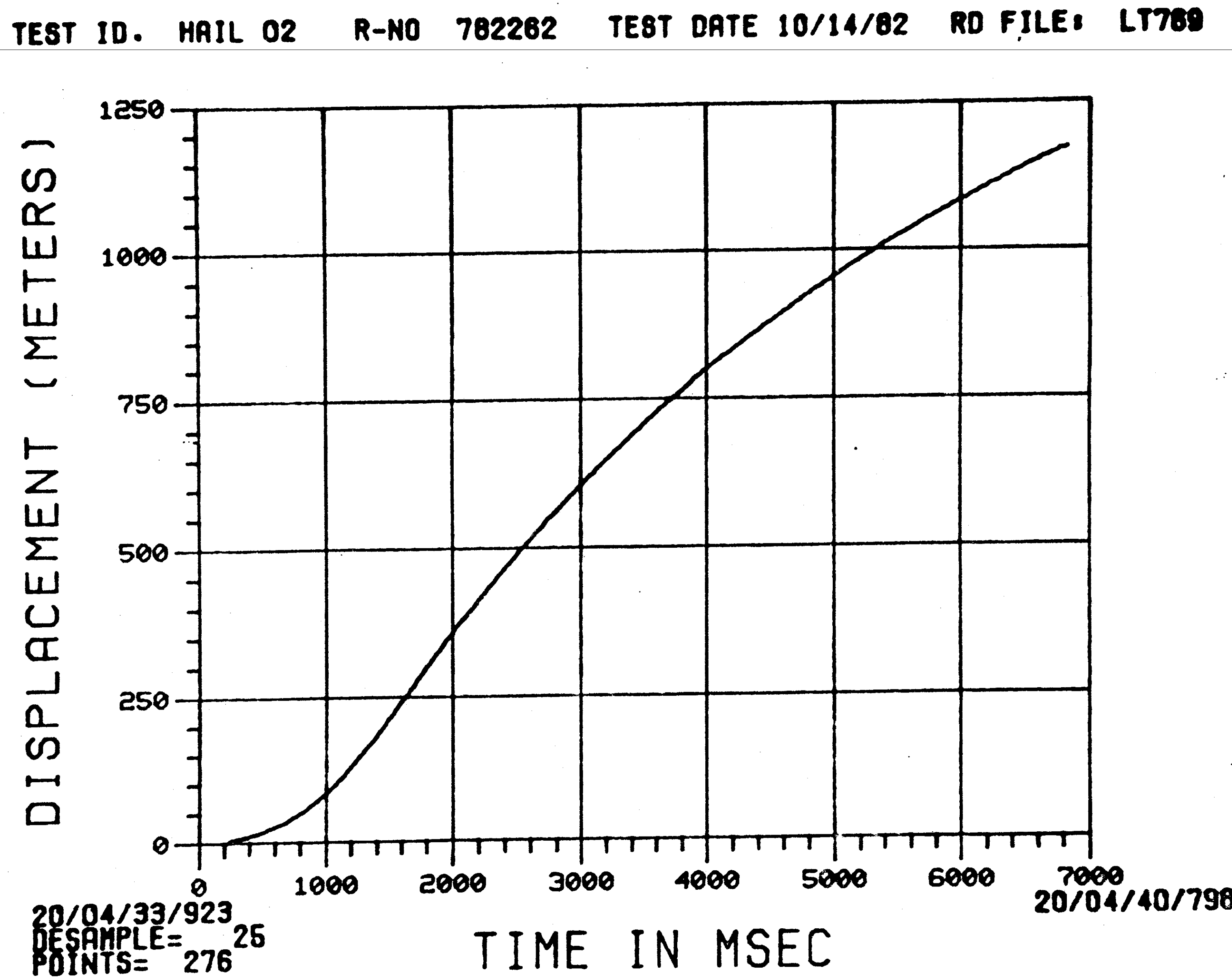

Figure 6. Displacement vs Time for Hail 02
Displacement $= [(x - x_o)^2 + (y - y_o)^2 + (z - z_o)^2]^{1/2}$

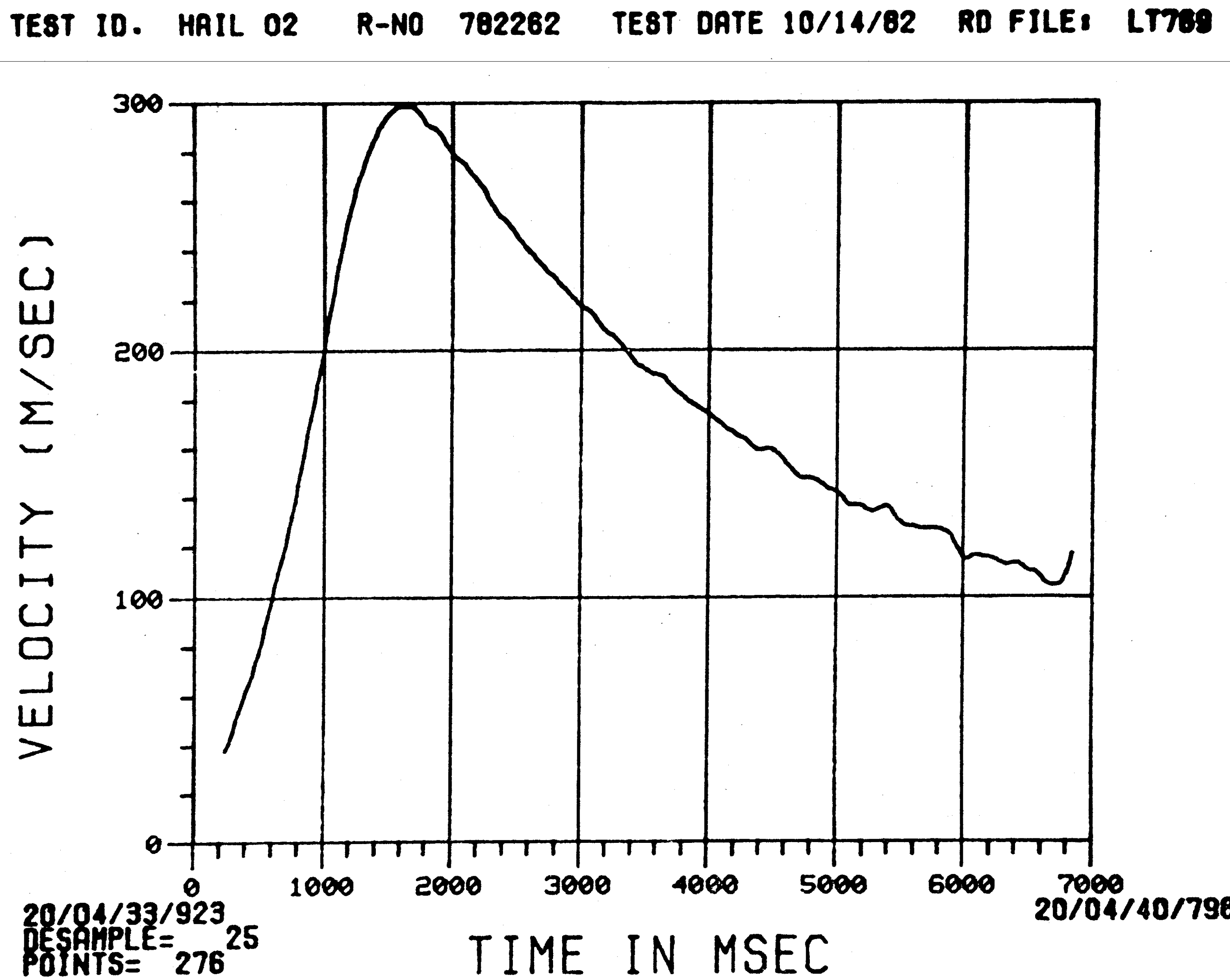

Figure 7. Displacement Velocity vs Time for Hail 02

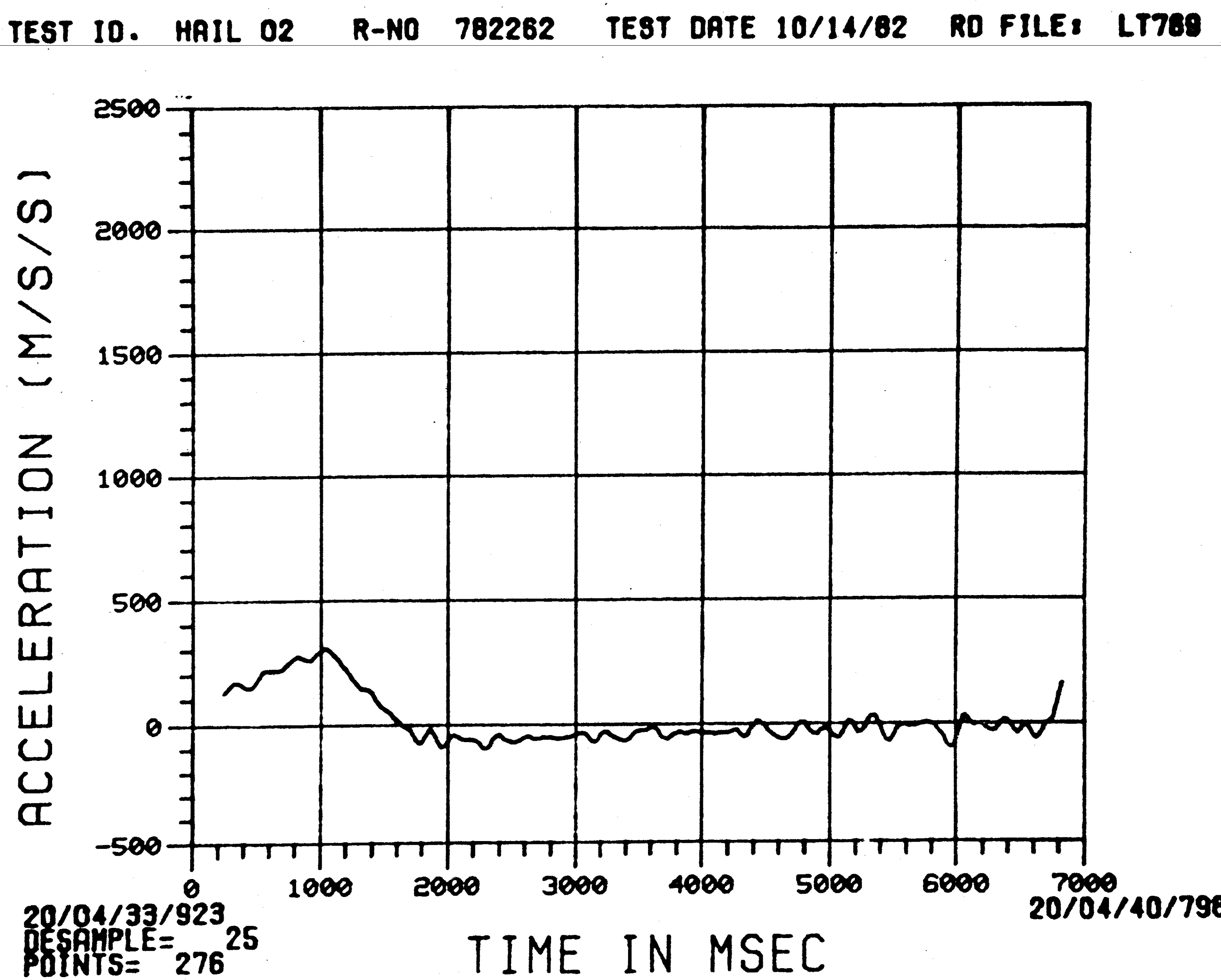

Figure 8. Displacement Acceleration for Hail 02

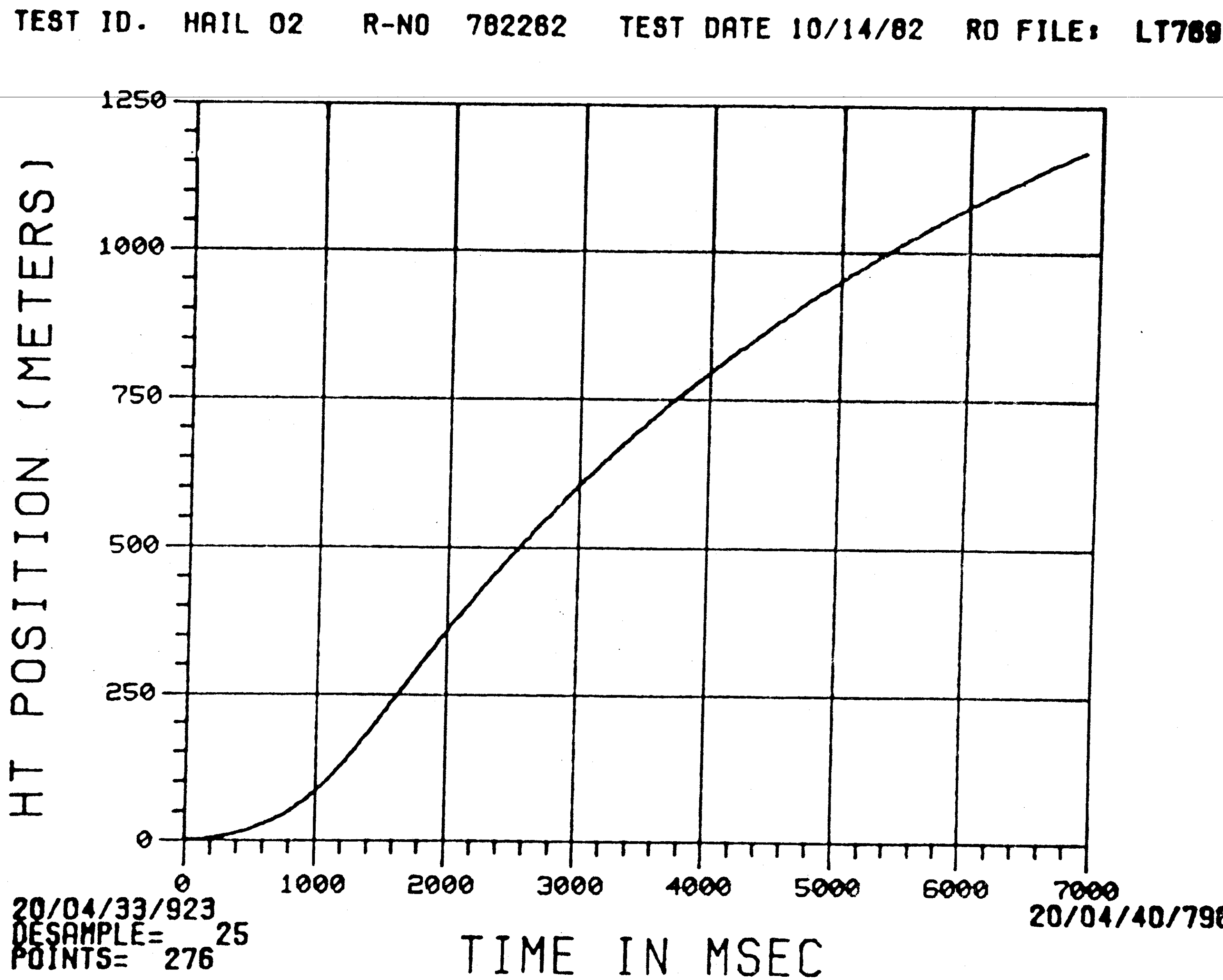

Figure 9. Height vs Time for Hail 02

results in Tables I and II together with secondarily-smoothed computation of velocity and acceleration for the indicated times after launch.

The smoothed velocity plots against height are shown in Figure 10 and the smoothed accelerations are plotted in Figure 11 where some correlation in the accelerations behavior of the two rockets may be noted.

We now turn to a quantitative examination of the rocket flights.

ESTIMATES OF ROCKET PROPERTIES

From Newton: $\vec{F} = d(m\vec{v})/dt$ (1)

In our case, for a rocket fired in an upward direction:

$$-mg - \text{drag force} = m(dv)/dt - v_{ex}\,(dm)/dt \qquad (2)$$

where m is mass of the rocket, g is the gravitation force/mass, v is the rocket velocity and v_{ex} is the velocity of the rocket exhaust. After rearranging Equation (2),

$$-\left(g + \frac{\text{drag force}}{m}\right) dt = dv - v_{ex}\, dm/m. \qquad (3)$$

If we assume that the drag force is described by $0.5\ C_d A \rho v^2$

where C_d is the rocket's drag coefficient,
A is the rocket's cross sectional area and
ρ is the density of the air,

we can estimate a drag coefficient from the rocket performance data after burnout of the fuel. In subsequent energy balances before apogee:

$$1/2\ m_f v_1^2 = 1/2\ m_f v_2^2 + m_f g \Delta h + 1/2\ C_d A \rho v^2 \Delta \ell \qquad (4)$$

where v_1 is the initial velocity at the base of a height

TABLE I

Kinematic Data Launched October 14, 1982

Hail 01 1335:22.128 M.S.T.

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s²)
50	-1.8	0.5	0.6		
75	-1.7	0.5	1.0		
100	-1.7	0.5	1.5		
125	-1.7	0.5	2.0	23	
150	-1.7	0.5	2.6	26	
175	-1.7	0.5	3.3	29	131
200	-1.7	0.5	4.0	33	144
225	-1.7	0.5	4.9	36	158
250	-1.6	0.4	5.8	40	165
275	-1.6	0.4	6.9	45	175
300	-1.6	0.4	8.1	49	177
325	-1.6	0.3	9.3	54	182
350	-1.6	0.3	10.7	58	185
375	-1.7	0.2	12.3	63	186
400	-1.7	0.0	13.9	68	192
425	-1.7	-0.2	15.6	72	197
450	-1.8	-0.3	17.5	77	206
475	-1.8	-0.5	19.4	83	220
500	-1.8	-0.8	21.5	88	230
525	-1.8	-1.0	23.8	94	239
550	-1.8	-1.3	26.2	100	248
575	-1.9	-1.6	28.8	107	254
600	-1.9	-1.9	31.5	113	261
625	-1.9	-2.2	34.4	120	266
650	-2.0	-2.6	37.4	126	272
675	-2.0	-3.0	40.7	133	280
700	-2.1	-3.4	44.1	140	289
725	-2.2	-3.8	47.6	148	299
750	-2.3	-4.2	51.4	155	308
775	-2.4	-4.7	55.3	163	315
800	-2.5	-5.2	59.4	171	321
825	-2.5	-5.7	63.8	179	328
850	-2.6	-6.2	68.4	187	338
875	-2.8	-6.8	73.1	196	345
900	-2.9	-7.4	78.1	205	355
925	-3.1	-8.0	83.2	214	371
950	-3.2	-8.7	88.6	223	379
975	-3.4	-9.3	94.3	233	389
1000	-3.6	-10.1	100.2	243	396
1025	-3.7	-10.8	106.3	253	389
1050	-3.9	-11.6	112.8	263	388
1075	-4.1	-12.4	119.4	272	381
1100	-4.3	-13.3	126.2	282	377
1125	-4.6	-14.2	133.4	291	371
1150	-4.8	-15.1	140.7	300	351
1175	-4.9	-16.1	148.2	309	337
1200	-5.2	-17.0	156.1	317	309
1225	-5.4	-18.0	164.0	324	271

Hail 01

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s²)
1250	-5.7	-19.0	172.2	331	240
1275	-5.9	-20.0	180.5	336	195
1300	-6.2	-21.1	188.9	341	157
1325	-6.5	-22.2	197.5	344	124
1350	-6.8	-23.2	206.1	347	94
1375	-7.1	-24.3	214.7	349	72
1400	-7.4	-25.4	223.4	350	48
1425	-7.7	-26.5	232.1	351	33
1450	-7.9	-27.5	240.8	352	17
1475	-8.2	-28.7	249.6	352	7
1500	-8.5	-29.7	258.3	352	-5
1525	-8.7	-30.9	267.0	352	-19
1550	-9.0	-32.0	275.8	351	-30
1575	-9.2	-33.1	284.5	350	-46
1600	-9.5	-34.2	293.2	349	-50
1625	-9.7	-35.3	301.8	347	-52
1650	-9.9	-36.4	310.4	346	-56
1675	-10.1	-37.5	318.9	345	-60
1700	-10.4	-38.5	327.4	343	-70
1725	-10.7	-39.6	335.9	341	-82
1750	-11.0	-40.6	344.4	339	-93
1775	-11.3	-41.7	352.9	337	-100
1800	-11.6	-42.7	361.2	334	-100
1825	-11.9	-43.8	369.4	331	-95
1850	-12.1	-44.9	377.5	329	-86
1875	-12.4	-45.9	385.6	327	-71
1900	-12.7	-46.9	393.7	325	-66
1925	-12.9	-47.9	401.8	324	-67
1950	-13.2	-48.9	409.8	322	-71
1975	-13.4	-49.9	417.8	320	-83
2000	-13.6	-51.0	425.7	318	-89
2025	-13.9	-52.0	433.6	316	-90
2050	-14.1	-52.9	441.4	314	-94
2075	-14.4	-53.9	449.1	311	-92
2100	-14.6	-54.9	456.8	309	-93
2125	-14.7	-55.9	464.4	307	-90
2150	-14.9	-56.9	472.0	304	-82
2175	-15.2	-57.9	479.5	302	-79
2200	-15.4	-58.8	487.0	301	-79
2225	-15.7	-59.8	494.4	299	-79
2250	-15.9	-60.7	501.7	296	-77
2275	-16.2	-61.7	509.1	294	-76
2300	-16.6	-62.5	516.4	293	-67
2325	-16.8	-63.5	523.6	291	-66
2350	-17.1	-64.4	530.8	290	-67
2375	-17.3	-65.3	538.0	288	-66
2400	-17.5	-66.2	545.0	286	-67
2425	-17.7	-67.1	552.2	285	-65
2450	-17.9	-68.1	559.2	283	-69
2475	-18.1	-69.0	566.1	281	-70
2500	-18.3	-69.9	573.1	279	-71

Hail 01

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s^2)
2525	-18.5	-70.8	580.0	278	-78
2550	-18.7	-71.7	586.9	276	-77
2575	-19.0	-72.6	593.7	274	-78
2600	-19.2	-73.4	600.5	272	-76
2625	-19.4	-74.3	607.2	270	-69
2650	-19.6	-75.2	613.8	268	-57
2675	-19.8	-76.0	620.4	267	-47
2700	-20.1	-76.9	627.0	266	-48
2725	-20.3	-77.7	633.6	265	-47
2750	-20.5	-78.6	640.2	263	-58
2775	-20.7	-79.4	646.7	262	-71
2800	-20.8	-80.3	653.2	260	-69
2825	-21.1	-81.2	659.6	258	-71
2850	-21.2	-82.0	666.0	257	-69
2875	-21.4	-82.8	672.3	255	-62
2900	-21.6	-83.6	678.5	253	-61
2925	-21.8	-84.5	684.8	252	-58
2950	-22.0	-85.3	691.1	250	-62
2975	-22.2	-86.1	697.2	249	-63
3000	-22.4	-86.9	703.4	247	-64
3025	-22.6	-87.7	709.5	246	-61
3050	-22.8	-88.5	715.6	244	-49
3075	-23.1	-89.3	721.5	243	-48
3100	-23.2	-90.2	727.5	242	-41
3125	-23.3	-91.0	733.5	241	-42
3150	-23.5	-91.7	739.5	240	-48
3175	-23.6	-92.5	745.5	239	-52
3200	-23.8	-93.3	751.3	237	-64
3225	-24.0	-94.1	757.2	235	-68
3250	-24.1	-94.9	763.0	234	-69
3275	-24.4	-95.7	768.8	232	-57
3300	-24.6	-96.4	774.5	231	-53
3325	-24.8	-97.1	780.2	230	-47
3350	-25.1	-97.9	785.8	228	-43
3375	-25.3	-98.6	791.5	227	-44
3400	-25.4	-99.4	797.2	226	-39
3425	-25.6	-100.2	802.7	225	-41
3450	-25.8	-100.9	808.3	224	-39
3475	-25.9	-101.7	813.8	223	-43
3500	-26.0	-102.4	819.3	222	-50
3525	-26.1	-103.2	824.8	221	-51
3550	-26.2	-104.0	830.3	219	-55
3575	-26.4	-104.8	835.7	218	-63
3600	-26.6	-105.5	841.1	217	-55
3625	-26.8	-106.2	846.4	215	-58
3650	-27.1	-106.9	851.7	214	-52
3675	-27.2	-107.6	857.0	212	-39
3700	-27.5	-108.3	862.2	212	-47
3725	-27.6	-109.0	867.5	211	-31
3750	-27.8	-109.7	872.7	209	-36
3775	-28.0	-110.4	877.8	209	-28

Hail 01

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s^2)
3800	-28.2	-111.2	883.0	208	-16
3825	-28.4	-111.9	888.1	208	-29
3850	-28.4	-112.6	893.3	208	-25
3875	-28.5	-113.4	898.4	206	-46
3900	-28.6	-114.1	903.5	206	-62
3925	-28.6	-114.8	908.7	203	-58
3950	-28.9	-115.5	913.6	201	-67
3975	-29.2	-116.1	918.6	201	-55
4000	-29.3	-116.8	923.5	199	-40
4025	-29.5	-117.5	928.3	198	-40
4050	-29.8	-118.2	933.3	197	-22
4075	-29.9	-118.9	938.2	197	
4100	-30.1	-119.5	943.0	197	
4125	-30.2	-120.2	947.9	195	

TABLE II

Kinematic Data — Hail 02

Launched October 14, 1982 — 1404:33.923 M.S.T.

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s²)
50	-0.0	-0.0	0.4		
75	0.0	-0.1	0.8		
100	-0.0	-0.0	1.2		
125	-0.0	0.0	1.7	20	
150	-0.1	0.0	2.2	22	
175	-0.2	0.0	2.7	25	109
200	-0.1	0.0	3.4	27	119
225	-0.1	0.0	4.1	31	131
250	-0.1	0.0	4.9	34	139
275	-0.1	0.0	5.8	38	146
300	-0.1	0.0	6.8	41	151
325	-0.1	0.1	7.8	45	154
350	-0.0	0.1	9.0	49	160
375	-0.0	0.1	10.3	53	159
400	-0.0	0.2	11.7	57	159
425	-0.1	0.4	13.2	61	161
450	-0.2	0.5	14.7	65	165
475	-0.2	0.7	16.4	69	175
500	-0.3	0.9	18.1	74	187
525	-0.3	1.1	20.0	79	200
550	-0.3	1.3	22.0	84	211
575	-0.4	1.6	24.1	89	217
600	-0.3	1.8	26.5	95	219
625	-0.4	2.0	28.9	100	219
650	-0.5	2.3	31.5	106	221
675	-0.6	2.5	34.2	111	224
700	-0.6	2.8	37.0	117	230
725	-0.7	3.1	39.9	123	236
750	-0.7	3.5	43.0	129	244
775	-0.8	3.8	46.3	135	252
800	-0.8	4.2	49.7	141	257
825	-0.9	4.6	53.3	148	262
850	-1.0	4.9	57.1	154	265
875	-1.1	5.3	61.0	161	267
900	-1.2	5.8	65.1	168	275
925	-1.4	6.2	69.3	175	280
950	-1.5	6.7	73.7	182	284
975	-1.6	7.2	78.3	189	288
1000	-1.8	7.8	83.1	196	292
1025	-1.9	8.3	88.1	203	295
1050	-2.1	8.8	93.3	211	295
1075	-2.2	9.4	98.6	219	289
1100	-2.4	9.9	104.1	226	281
1125	-2.7	10.6	109.8	232	269
1150	-2.8	11.2	115.7	239	257
1175	-3.1	11.9	121.7	245	247
1200	-3.3	12.6	127.9	251	231
1225	-3.4	13.3	134.2	257	214

Hail 02

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s²)
1250	-3.6	13.9	140.6	262	196
1275	-3.7	14.6	147.2	267	180
1300	-4.0	15.4	154.0	271	167
1325	-4.2	16.1	160.8	275	148
1350	-4.5	16.8	167.6	279	136
1375	-4.8	17.6	174.6	282	127
1400	-5.0	18.4	181.6	285	110
1425	-5.4	19.2	188.8	288	106
1450	-5.6	19.9	195.9	290	95
1475	-6.0	20.7	203.2	292	79
1500	-6.3	21.5	210.5	294	71
1525	-6.5	22.3	217.8	296	51
1550	-6.8	23.1	225.2	297	44
1575	-7.1	23.9	232.6	297	33
1600	-7.4	24.7	240.0	298	17
1625	-7.8	25.6	247.4	299	16
1650	-8.2	26.4	254.8	299	-0
1675	-8.5	27.2	262.2	299	-15
1700	-8.8	28.0	269.7	298	-28
1725	-9.1	28.8	277.1	297	-50
1750	-9.3	29.6	284.5	296	-59
1775	-9.6	30.4	291.9	294	-62
1800	-9.9	31.2	299.1	293	-57
1825	-10.2	32.0	306.3	291	-43
1850	-10.5	32.8	313.5	290	-45
1875	-10.8	33.6	320.7	290	-49
1900	-11.2	34.4	327.9	288	-57
1925	-11.5	35.2	335.1	286	-76
1950	-11.8	36.0	342.2	284	-79
1975	-12.0	36.8	349.2	282	-81
2000	-12.2	37.6	356.1	280	-70
2025	-12.5	38.3	363.0	278	-57
2050	-12.7	39.1	369.9	277	-53
2075	-12.9	39.8	376.8	276	-47
2100	-13.2	40.6	383.7	275	-56
2125	-13.4	41.3	390.5	274	-67
2150	-13.8	42.1	397.3	272	-67
2175	-14.1	42.9	404.0	270	-70
2200	-14.3	43.6	410.6	268	-74
2225	-14.6	44.3	417.3	266	-77
2250	-14.8	45.1	423.9	264	-85
2275	-15.1	45.8	430.5	262	-87
2300	-15.4	46.6	437.0	260	-89
2325	-15.6	47.3	443.4	258	-79
2350	-15.9	48.0	449.7	256	-69
2375	-16.2	48.8	456.0	254	-64
2400	-16.4	49.4	462.3	253	-49
2425	-16.7	50.2	468.5	251	-50
2450	-16.9	50.9	474.8	251	-57
2475	-17.1	51.5	481.0	249	-60
2500	-17.4	52.2	487.1	247	-67

Hail 02

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s^2)
2525	-17.7	53.0	493.3	245	-67
2550	-17.9	53.7	499.4	244	-65
2575	-18.1	54.3	505.3	243	-65
2600	-18.4	55.0	511.4	241	-62
2625	-18.7	55.7	517.3	239	-70
2650	-18.9	56.4	523.2	238	-60
2675	-19.1	57.1	529.1	236	-50
2700	-19.4	57.7	534.9	235	-56
2725	-19.5	58.4	540.7	234	-48
2750	-19.7	59.0	546.5	232	-52
2775	-19.9	59.7	552.3	231	-60
2800	-20.1	60.3	558.1	229	-66
2825	-20.4	61.0	563.7	228	-74
2850	-20.6	61.7	569.3	226	-75
2875	-20.9	62.3	574.9	223	-74
2900	-21.1	62.9	580.4	222	-62
2925	-21.3	63.6	585.8	221	-50
2950	-21.6	64.2	591.3	219	-46
2975	-21.8	64.9	596.7	218	-46
3000	-22.0	65.5	602.2	217	-43
3025	-22.3	66.1	607.5	216	-40
3050	-22.5	66.7	612.9	215	-46
3075	-22.7	67.4	618.2	214	-49
3100	-22.9	68.0	623.5	213	-45
3125	-23.1	68.6	628.7	211	-49
3150	-23.3	69.2	634.1	210	-45
3175	-23.4	69.8	639.2	209	-46
3200	-23.6	70.4	644.3	208	-52
3225	-23.8	71.0	649.5	207	-54
3250	-24.1	71.6	654.6	205	-57
3275	-24.3	72.2	659.7	204	-52
3300	-24.4	72.8	664.8	203	-53
3325	-24.6	73.4	669.8	201	-56
3350	-24.8	74.0	674.7	200	-52
3375	-25.0	74.5	679.7	198	-47
3400	-25.2	75.2	684.6	197	-41
3425	-25.4	75.7	689.5	197	-39
3450	-25.6	76.3	694.3	196	-42
3475	-25.8	76.9	699.1	195	-42
3500	-26.0	77.5	704.0	193	-40
3525	-26.2	78.0	708.8	192	-41
3550	-26.4	78.6	713.6	192	-35
3575	-26.6	79.2	718.2	191	-38
3600	-26.8	79.8	723.0	190	-36
3625	-27.0	80.3	727.7	189	-34
3650	-27.1	80.9	732.3	188	-38
3675	-27.2	81.4	737.1	187	-41
3700	-27.4	82.0	741.7	186	-55
3725	-27.5	82.5	746.3	185	-54
3750	-27.7	83.1	750.8	183	-54
3775	-27.9	83.6	755.3	182	-53
3800	-28.1	84.2	759.8	180	-43
3825	-28.4	84.8	764.2	179	-44
3850	-28.5	85.3	768.7	178	-37
3875	-28.7	85.8	773.1	177	-38
3900	-28.9	86.4	777.5	177	-36
3925	-29.0	86.9	781.9	175	-33
3950	-29.2	87.4	786.2	175	-33
3975	-29.4	88.0	790.5	174	-23
4000	-29.6	88.5	794.8	173	-25
4025	-29.8	89.1	799.1	173	-26
4050	-30.0	89.6	803.4	172	-33
4075	-30.2	90.1	807.7	171	-38
4100	-30.3	90.6	811.9	170	-43
4125	-30.4	91.1	816.1	169	-43
4150	-30.6	91.7	820.3	168	-37
4175	-30.8	92.2	824.4	167	-42
4200	-30.9	92.7	828.6	166	-35
4225	-31.1	93.2	832.7	165	-40
4250	-31.2	93.7	836.8	164	-45
4275	-31.3	94.2	840.9	163	-44
4300	-31.5	94.7	844.9	162	-43
4325	-31.6	95.2	848.9	161	-25
4350	-31.9	95.7	852.8	160	-26
4375	-32.1	96.2	856.7	161	-20
4400	-32.3	96.7	860.7	159	-20
4425	-32.5	97.2	864.7	159	-36
4450	-32.7	97.7	868.7	158	-34
4475	-32.8	98.2	872.6	157	-40
4500	-32.8	98.7	876.4	156	-36
4525	-33.1	99.2	880.3	155	-39
4550	-33.3	99.7	884.0	155	-28
4575	-33.5	100.1	887.9	153	-22
4600	-33.7	100.7	891.7	153	-37
4625	-33.7	101.1	895.5	153	-32
4650	-33.8	101.6	899.2	151	-47
4675	-33.9	102.0	903.0	150	-37
4700	-34.1	102.5	906.7	148	-28
4725	-34.3	103.0	910.3	149	-19
4750	-34.5	103.5	914.0	148	-4
4775	-34.7	104.0	917.6	148	-26
4800	-34.7	104.4	921.3	148	-22
4825	-34.8	104.9	925.1	146	-38
4850	-35.0	105.3	928.7	146	-55
4875	-35.0	105.8	932.4	144	-48
4900	-35.3	106.2	935.8	143	-53
4925	-35.6	106.7	939.3	141	-33
4950	-35.8	107.2	942.8	141	-14
4975	-36.0	107.7	946.2	141	-4
5000	-36.1	108.1	949.7	141	-5
5025	-36.2	108.6	953.2	141	-15
5050	-36.4	109.0	956.7	140	-24

Hail 02

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s²)
5075	-36.4	109.4	960.3	139	-37
5100	-36.6	109.9	963.7	139	-35
5125	-36.8	110.3	967.1	137	-35
5150	-36.8	110.8	970.5	137	-29
5175	-37.0	111.2	973.9	136	-19
5200	-37.1	111.6	977.2	136	-18
5225	-37.1	112.1	980.6	136	-17
5250	-37.3	112.5	984.0	135	-29
5275	-37.4	112.9	987.3	134	-34
5300	-37.5	113.4	990.6	133	-28
5325	-37.8	113.8	993.9	132	-37
5350	-38.0	114.3	997.1	132	-27
5375	-38.2	114.7	1000.3	131	-21
5400	-38.3	115.1	1003.6	130	-23
5425	-38.4	115.5	1006.9	130	-12
5450	-38.5	116.0	1010.0	130	-17
5475	-38.7	116.4	1013.2	129	-19
5500	-38.9	116.8	1016.4	129	-28
5525	-39.0	117.3	1019.6	128	-26
5550	-39.2	117.7	1022.8	127	-27
5575	-39.4	118.1	1025.9	127	-29
5600	-39.4	118.5	1029.0	126	-13
5625	-39.6	118.9	1032.1	125	-20
5650	-39.6	119.4	1035.3	126	-8
5675	-39.7	119.8	1038.3	125	-8
5700	-39.8	120.2	1041.4	125	-27
5725	-39.9	120.5	1044.6	124	-20
5750	-40.1	120.9	1047.6	123	-33
5775	-40.3	121.4	1050.7	123	-21
5800	-40.4	121.8	1053.7	122	-8
5825	-40.6	122.2	1056.5	122	-9
5850	-40.6	122.6	1059.6	122	6
5875	-40.6	123.0	1062.7	122	-13
5900	-40.6	123.3	1065.8	122	-29
5925	-40.6	123.7	1068.9	121	-43
5950	-40.8	124.1	1071.9	119	-64
5975	-40.9	124.5	1074.8	118	-69
6000	-41.0	124.9	1077.6	116	-54
6025	-41.3	125.4	1080.4	114	-45
6050	-41.4	125.8	1083.2	114	-41
6075	-41.5	126.2	1086.1	113	-13
6100	-41.9	126.6	1088.8	112	-18
6125	-41.9	127.0	1091.6	113	3
6150	-42.2	127.4	1094.4	112	10
6175	-42.5	127.8	1097.0	113	-1
6200	-42.5	128.2	1099.9	113	12
6225	-42.6	128.6	1102.7	113	-21
6250	-42.7	129.0	1105.6	113	-26
6275	-42.7	129.4	1108.4	111	-40
6300	-42.9	129.8	1111.1	110	-48
6325	-43.0	130.1	1113.8	109	-15

Hail 02

Time after launch(ms)	x (m)	y (m)	z (m)	velocity (m/s)	accel (m/s²)
6350	-43.1	130.5	1116.4	109	-4
6375	-43.3	130.9	1119.0	110	18
6400	-43.5	131.3	1121.7	110	13
6425	-43.5	131.7	1124.5	111	-1
6450	-43.6	132.1	1127.4	110	-6
6475	-43.6	132.4	1130.2	110	-22
6500	-43.7	132.8	1132.8	109	-36
6525	-43.8	133.2	1135.4	108	-37
6550	-44.0	133.5	1138.0	106	-57
6575	-44.0	133.9	1140.8	106	-57
6600	-43.9	134.3	1143.5	104	-43
6625	-44.3	134.7	1145.9	103	-56
6650	-44.4	135.1	1148.5	102	-25
6675	-44.7	135.5	1150.7	100	
6700	-45.0	135.8	1153.2	101	
6725	-45.0	136.1	1155.9	101	

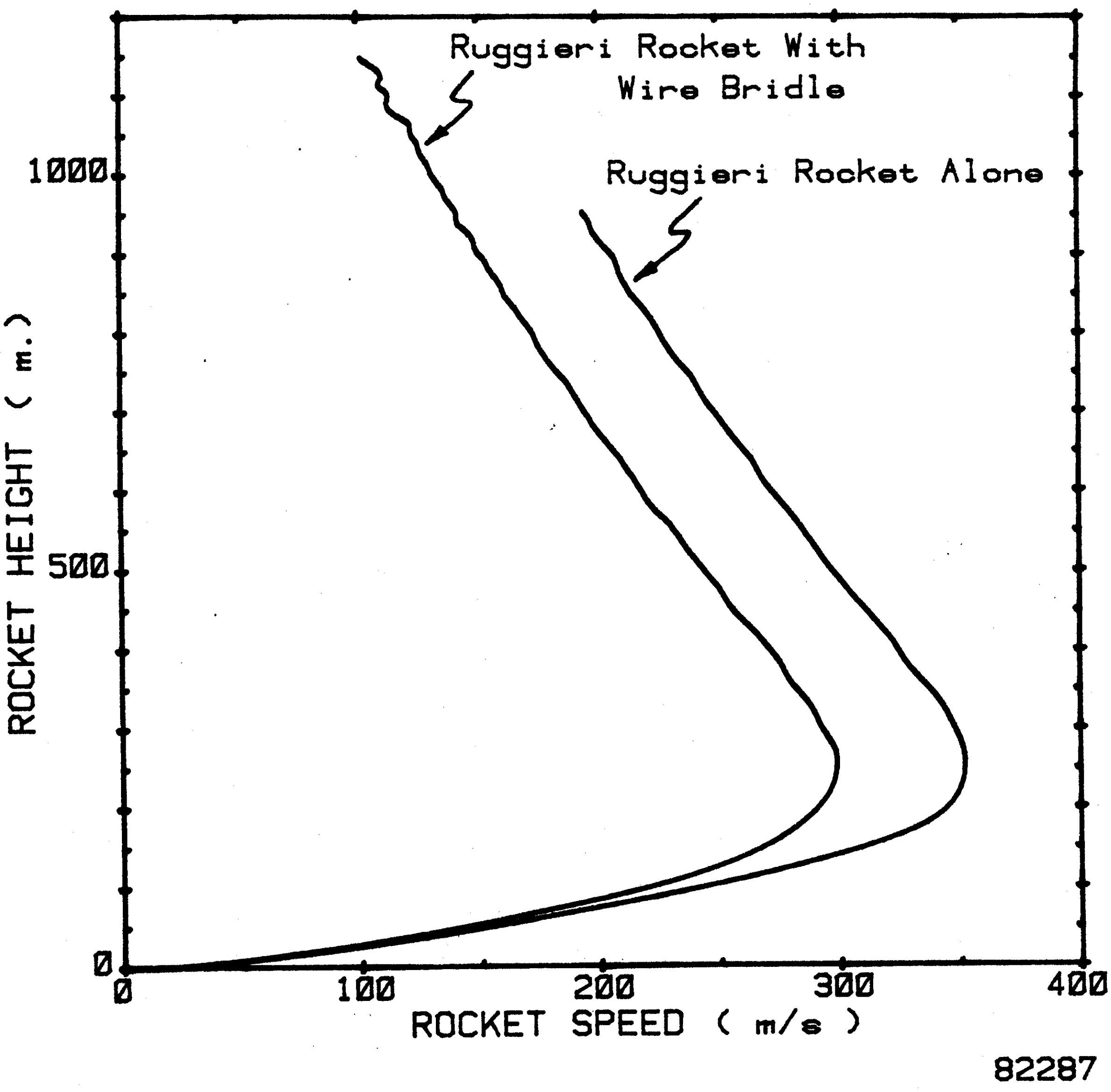

Figure 10. Smoothed displacement-speed plots versus rocket height for Hail 01 (Rocket Alone) and Hail 02 (Rocket with Bridle)

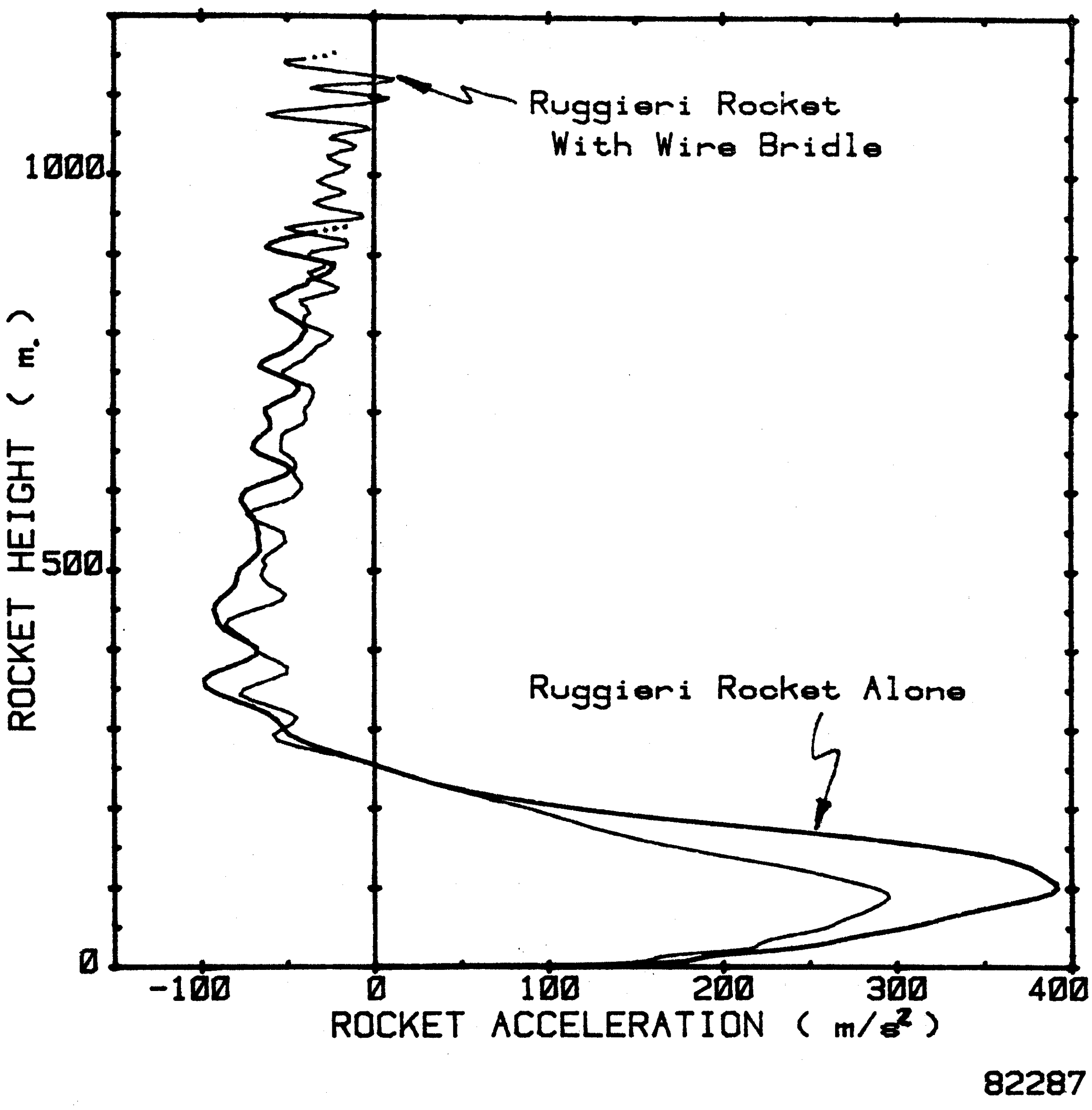

Figure 11. Smoothed displacement-acceleration plots versus rocket height for Hail 01 (Rocket Alone) and Hail 02 (Rocket with Bridle)

interval $\triangle h$, v_2 is the velocity at the top of the interval, m_f is the rocket mass after burnout, and $\triangle \ell$ is the path length increment.

Therefore,

$$C_d \simeq \frac{2[v_1^2 - v_2^2 - 2g\triangle h]m_f}{\rho A\ [v_1^2 + v_2^2]\triangle \ell} . \qquad (5)$$

The smoothed velocity and position data were used in the calculation of drag coefficient together with air densities computed for each height in a neutrally stable atmosphere with the nominal initial surface conditions (atmospheric pressure of 850 mb and air temperature of 20°C). The rocket dimensions and masses used are listed in Table III. Plots of calculated values for the drag coefficient, C_d, against height are shown in Figures 12 and 13 for the two rockets. Variations in the calculated values reflect the oscillations shown in the acceleration curves and therefore show some of the uncertainities in the data arising from jitter in the tracker. A few of the apparent decreases in drag coefficent, however, may be attributed to the bursts of smoke observed after the principal fuel was burned: any emissions at these later times would act to produce thrust and to reduce drag.

The mean value for the Hail 01 drag coefficient for the height interval between 330 m and 930 m is 0.45 with a standard deviation of 0.10. The similar value for Hail 02 (with its trailing bridle) over the altitude interval between 400 m and 1000 m is 0.55 with a standard deviation of 0.13.

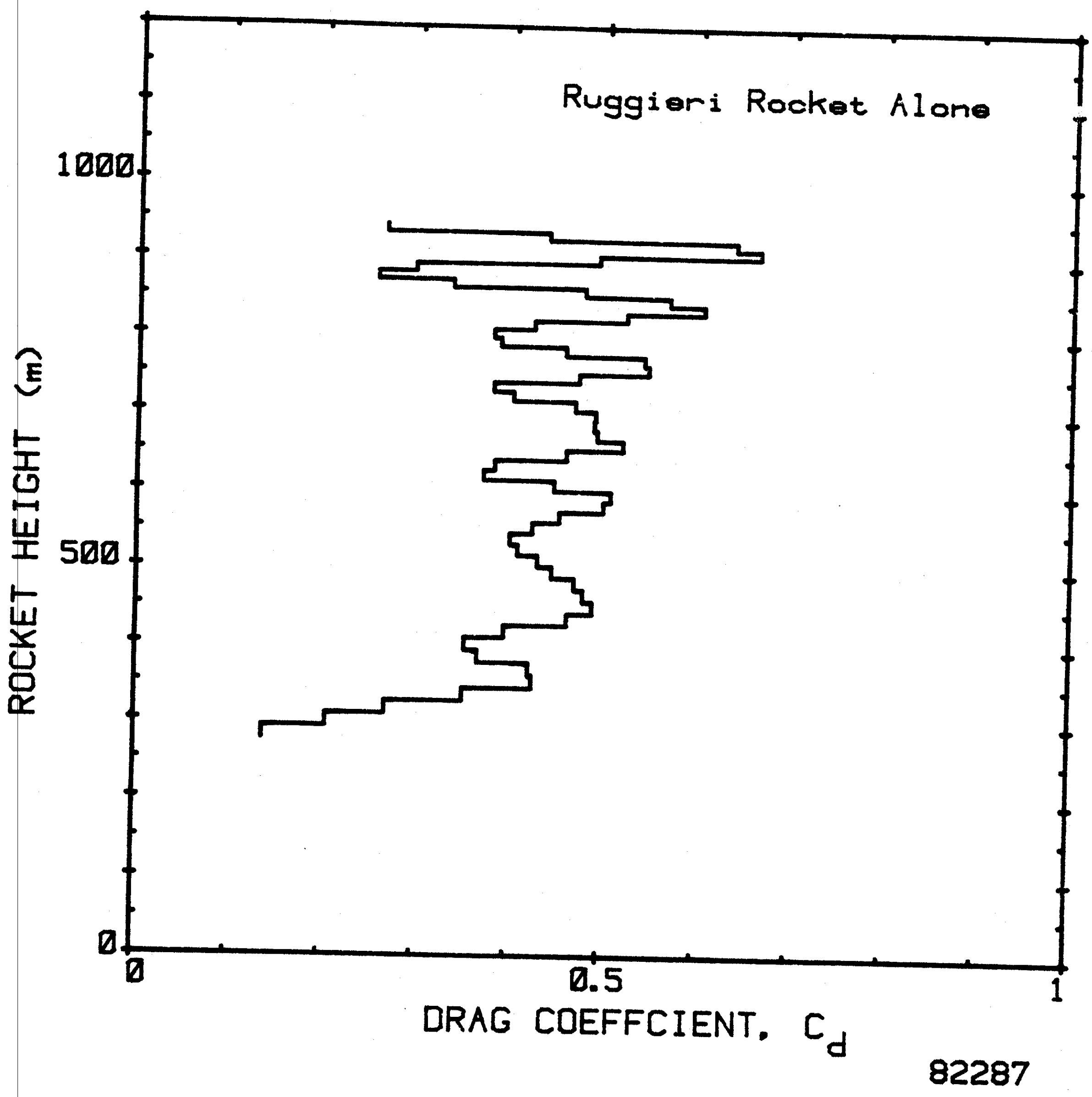

Figure 12. Calculated drag coefficients versus rocket height for Hail 01. The mean coefficient for the height interval between 330 m and 930 m is 0.45 with a standard deviation of 0.10.

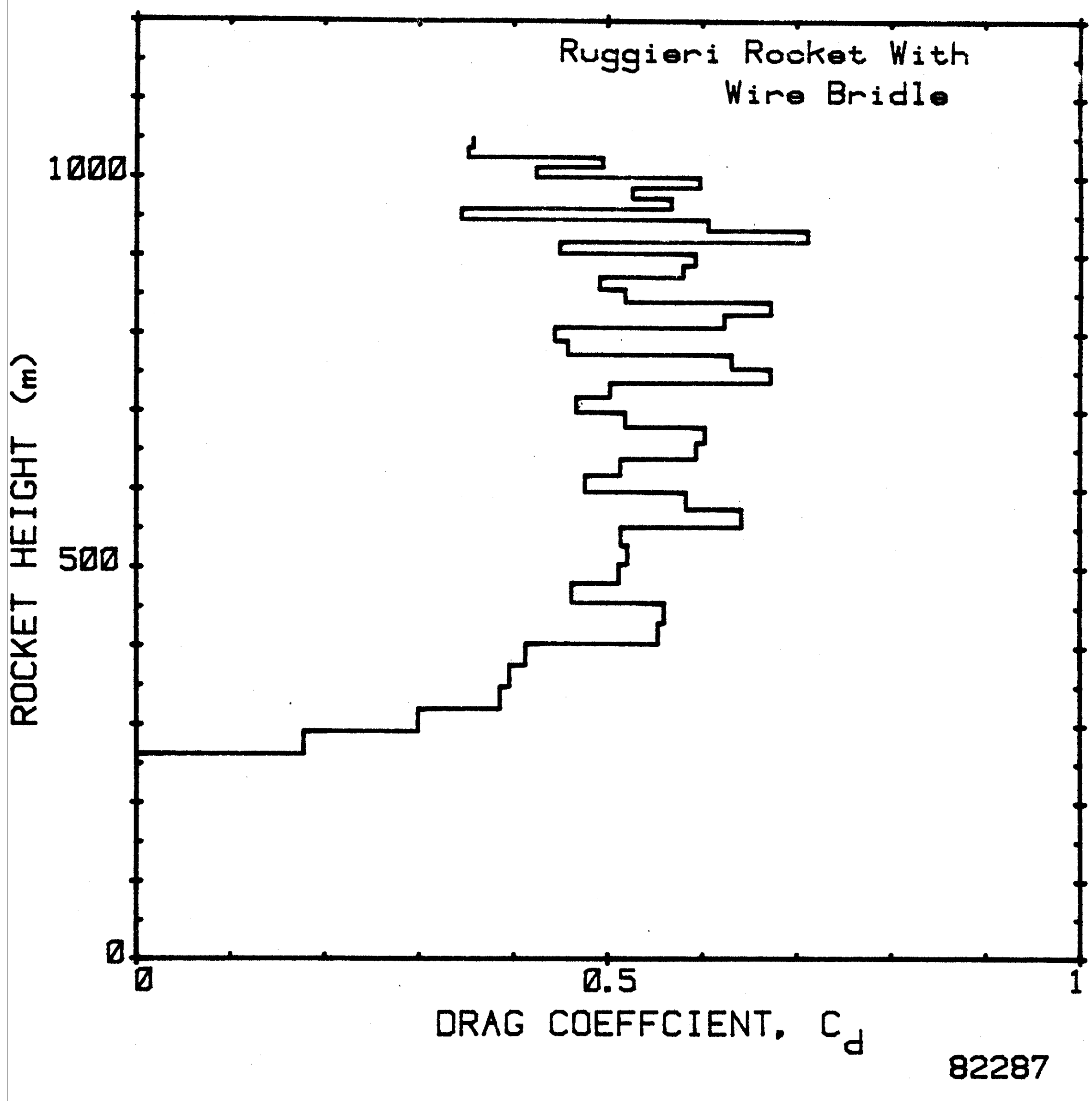

Figure 13. Calculated drag coefficients versus height for Hail 02. The mean coefficient for the height interval between 400 m and 1000 m is 0.55 with a standard deviation of 0.13.

We can now estimate the impulse due to the drag force acting on the rocket over the period of thrust, τ, if we assume the drag relation and the drag calculated coefficient to be applicable and constant over the earlier time interval.

We define $\sum_{\tau} (1/2 C_d A \overline{[v(t)]}^2 \Delta t)$

as the drag force impulse, $\overline{F}_d \tau$ and find that it has a value about 85 N s for Hail 01. The drag coefficient during the period of combustion may actually be less than inferred here, owing to the different flow conditions at the back of the rocket. As a result, the drag impulse during the sub-sonic portions of the flight may similarly be less than estimated here. With the worst case data, we can estimate an upper limit for the mean exhaust velocity by integrating Equation (3) over the period of thrust τ:

$$- [g + (\overline{F_d/m})]\tau = V_f - v_{ex} \ln(m_f/m_i)$$

so that

$$|\overline{v_{ex}}| \leqslant \frac{v_f + [g + (\overline{F}_d/m)]\tau}{\ln(m_i/m_f)} .$$

(F_d/m) was about 60 m/sec^2 for Hail 01, and $\ln(m_i/m_f)$ was 0.68 for Hail 01 and Hail 02, so that $|v_{ex}|$ was about 660 m/s.

The impulse provided to the rocket body is estimated by using equation (2) differently, with m(dv/dt), defined as the upward force exerted on the rocket body by its motor.

Therefore,

$$\int F_{rocketbody}\, dt = \int_{m_i}^{m_f} v_{ex} dm - \int_0^{\tau} (mg + F_d) dt.$$

TABLE III

SOME OF THE CHARACTERISTICS OF THE RUGGIERI ROCKETS DETERMINED IN THESE TESTS

Length:		84 cm	
Body Diameter:		6.5 cm	
Fin Area:		320 cm^2	
Mass:			
Rocket Motor			
Body:	859 gm		
Fuel:	941 gm		
Motor Total:			1800 gm
Nose Cone			108 gm
Total:			1908 gm

Thrust Duration: 1.5 to 1.7 seconds

Mean exhaust velocity: 660 m/s

Motor Impulse: 640 Newton seconds

Maximum Upward Velocity: 350 m/s

Nominal Apogee (without wire): 1800 m

Drag coefficient (immediately after burnout and without trailing wire): 0.45 with a standard deviation of 0.10

The net upward impulse,

$$\int F_{rocketbody}\, dt = |\overline{v_{ex}}|\ (m_i - m_f) - (\overline{m}g + \overline{F}_d)\tau \ .$$

The impulse provided by the rocket motor is therefore given by $|\overline{v_{ex}}|\,(m_i - m_f)$ and had a value of about 640 N s for Hail 01. The magnitude of the combined gravitation and drag force impulse is estimated as about 100 N s for this test. Therefore, the impulse available for accelerating the rocket is about 540 N s.

The specific impulse, I_{sp}, of a rocket-fuel is defined as the thrust force, F_t, produced by a unit weight of propellant burned per unit time: $I_{sp} \equiv F_t/d(mg)/dt$. This is equivalent to

$$\overline{I}_{sp} = \frac{\overline{F}_t \Delta t}{g \Delta m} \simeq \frac{|\overline{v_{ex}}|}{g} \ .$$

We infer a mean specific impulse of the order of 65 seconds for the Ruggieri propellant. This value is about 1/4 that used in high-performance, military rocket fuels where specific impulses of the order of 250 seconds are commonly used. The results of these tests are listed in Table III.

CONCLUSIONS

1. From the measurements obtained during these tests, we find that the period of thrust is of the order of 1.5 to 1.7 seconds, much shorter than the duration of smoke emissions which is of the order of 5 seconds or longer.

2. The rocket motor impulse is of the order of 640 Newton-seconds.

3. The mean drag coefficient for the vehicle is about 0.45, after burnout when no wires are being towed.

4. The peak accelerations given to a trailing wire are of the order of 30 g so that considerable stress is placed on the wire even with these rockets of modest performance. Breaking lengths of less than 1000 m may be expected under these accelerations.

5. The French rockets trigger lightning quite early in their flight so that, probably, rockets of appreciably less impulse could have the altitudes and velocity performance necessary to trigger lightning with grounded wires. Use of less powerful rockets will decrease the occurrence of wire breakage and, therefore, within limits, may increase the probability of triggering lightning on a given firing.

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3-9 (30)

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