A New Slip Monitor for Traction Equipment

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ABSTRACT

A new noncontact technique for monitoring the slip of agricultural traction devices is described. The method is based on the application of modern solid-state microwave Doppler radar to measure the true ground velocity of the tractor and the circumferential velocity of the drive wheel. A technique of monitoring the angular velocity of the drive wheel with a tachometer, and of measuring the ground velocity of the tractor using a fifth wheel assembly was used as the conventional slip measuring method. Experimental results obtained during the field tests and analyzed in the laboratory are presented. The results show that slips measured by Doppler radars are generally in good agreement with those measured by a conventional method.

INTRODUCTION

Slip or travel reduction is of interest when agricultural tractors pull a drawbar load. Reducing or controlling slip of traction devices for agricultural machinery results in better tractive efficiency, conserves fuel and reduces tire wear and capital costs.

Tractor operators need a simple method for determining the amount of traction device slip under field conditions. Slip should not be excessive in order to obtain maximum tractive efficiency and to reduce tire wear. Generally maximum tractive efficiency occurs when the driving wheels slip between 10 and 15 percent (Barger et al., 1963). Tractive efficiency will be reduced from the maximum value expected if slip is too low or too high. Proper ballasting of tractors or proper gear selection would be facilitated if a reliable and easy to use slip meter were made available for tractors.

Several popular methods of measuring slip are based on counting the number of drive-wheel revolutions required for the traction equipment to travel a given distance under no load and again under steady load conditions. These methods are cumbersome and time consuming and do not provide information about instantaneous values of slip. Various studies have been made in an effort to measure and control drive-wheel slip of agricultural tractors (Paulson and Zoerb, 1971; Paulson and Elliott, 1974; Zoerb et al., 1971; and Zoerb and Popoff, 1967). However, none of the methods used in the past have proven to be of practical use to tractor operators.

Microwave Doppler radar has been used for many years in navigation, traffic control and intruder detection applications. Its capabilities and limitations in these applications have been studied in great detail (Skolnik, 1962). Its application as a speedometer has been reported recently (Grimes and Jones, 1974 and Hyltin et al., 1973). Doppler radar can be used to measure ground speed of automobiles and other land vehicles regardless of the type of surface or the surface condition over which the vehicle traverses. The low cost, simplicity and high reliability of modern solid-state microwave Doppler radars make their application in monitoring traction device slip very attractive form both a technical and an economic point of view (Agriculture Canada, DSS, 1976; Thansandote, 1976 and Stuchly et al., 1975).

PRINCIPLE OF OPERATION

In the continuous wave (CW) Doppler radar the transmitter sends out continuous electromagnetic signal and the receiver also continuously detects the return signal, which carry information on the relative velocity of the radar in respect to the reflecting target, due to the Doppler effect (Hamid and Stuchly, 1975). The Doppler effect is well known in sound applications. As the radar moves relative to the reflecting target, the change in path length for the transmitted and returned signals produces a change of frequency of the return signal with respect to the transmitted signal. The Doppler frequency, which is the difference between the frequency of the transmitted and returned signals, is directly proportional to the radar velocity towards or away from the reflecting target. The Doppler radar principle as applied to the vehicle velocity measurement with respect to ground is illustrated in Fig. 1. Mathematically, the velocity can be expressed as

$$V = \frac{\lambda}{2\cos\Theta} \cdot f_d \qquad [1]$$

where

V = the velocity of the vehicle in m/s,
λ = the transmitted wavelength in m,
Θ = the antenna viewing angle, and
f_d = the Doppler frequency in Hz.

For example, for an antenna viewing angle of 45 deg and a typical transmitter frequency of 10.525 GHz, the velocity of one km/h is equivalent to the Doppler frequency of 13.78 Hz.

Article was submitted for publication in July 1976; reviewed and approved for publication by the Power and Machinery Division of ASAE in May 1977. Presented as ASAE Paper No. 76-1070.

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Acknowledgments: The authors would like to thank Professor M. Yunik for his numerous helpful suggestions and discussions during this research work, and J. G. Putnam for his assistance in the preparation of the instrument mounts for the experiments. Appreciation is also given to Agriculture Canada and for financial assistance.

Most microwave velocity meters for vehicluar applications use a solid-state oscillator as a transmitter. The microwave energy is radiated by the antenna to strike the ground surface at an angle with respect to the surface. A small fraction of the transmitted energy is returned through the same antenna to the mixer. The transmitter also acts as a local oscillator and may or may not be the mixer as well. The Doppler signal at the output of the mixer is at a frequency proportional to the vehicle ground speed.

A basic expression for slip is given by

$$S = \frac{(V_o - V)}{V_o} \qquad [2]$$

where

S = the slip,

V = the velocity of tractor at slip S and

V_o = the initial or no load velocity (Gill and Vanden Berg, 1967).

The above expression defines slip for the traction vehicle rather than the traction device. Defining slip for the traction device is a difficult problem and no practical method exists for measuring this parameter. The above expression appears relatively straightforward and indeed is the definition usually used. In reality the problem of measuring slip in the vehicle sense is complicated by the fact that the no load slip for a pneumatic tire is difficult to define and measure.

The concept of the Doppler radar slip monitor is based on using two Doppler radars to measure the true ground velocity of the tractor and the circumferential velocity of the drive wheel. The frequencies f_{d_1} and f_{d_2} (Fig. 2) of the signals at the output of Doppler radars carry the information about the true ground velocity (V_g) and the circumferential velocity (V_c). The difference between these velocities normalized to the circumferential velocity is equal to the slip (equation [2]).

EXPERIMENTAL ARRANGEMENTS

In this research, a commercially available low-cost microwave Doppler transceiver Model MA-86656A (Microwave Associates Inc.) was chosen and used as a main sensing element. The device operates at a frequency of 10.525 GHz and requires a power supply of 7.5 V at 120 mA (DC). It has an output power of approximately 10 mW.

A conical horn antenna was selected as a main radiator. This antenna is compact in size (length 230 mm) and has a high gain (21 dB) and a narrow beamwidth (approx. 15 deg). The antenna was located close to the center of gravity of the tractor in order to minimize the effects of tilt and vibration of the vehicle (Agriculture Canada, DSS, 1976). The recommended antenna viewing angle is in the range of 20 to 45 deg. Small viewing angles are desirable to minimize the influence of noise and the effects of tractor vibrations. From the point of view of the backscattering properties of the terrain, viewing angles of less than 15 deg are not recommended. The Doppler radar required an operating voltage of 7.5 V whereas the tractor battery voltage usually ranges from 10 to 14 V. Thus, the Doppler module was powered directly from the tractor battery through a voltage regulator.

A first set of experiments reported in this paper was performed with a Massey-Ferguson model 150 tractor. Two Doppler modules equipped with horn antennae were attached to a bracket in front of a drive wheel for field tests (Fig. 3). One horn antenna was directed to the ground, the other was directed to the tire. The modules provided Doppler signals of frequencies proportional to the true ground velocity of the tractor and the circumferential velocity of the drive wheel.

The ground velocity was also monitored by an additional wheel (fifth wheel) associated with a magnetic pickup probe, and by a mechanical system consisting of a measuring tape, with small holes punched 0.9 m apart and with one end anchored to a steel block (Fig. 4). When the tractor moved the tape unwound through a photoelectrical system and the electrical pulses of frequency f_{g_1} proportional to the true ground velocity were produced. The magnetic pickup probe provided an electrical signal of frequency f_{g_1} proportional to the angular velocity of the fifth wheel and hence to the true ground velocity of the tractor. The angular velocity of the drive wheel was monitored by a Microswitch activated by a 36-tooth sprocket attached to the drive wheel. The frequency f_{RPM} of the electrical pulses produced by the Microswitch was proportional to the angular velocity of the drive wheel.

In order to reduce the number of instruments installed on the tractor during field tests, the signals from

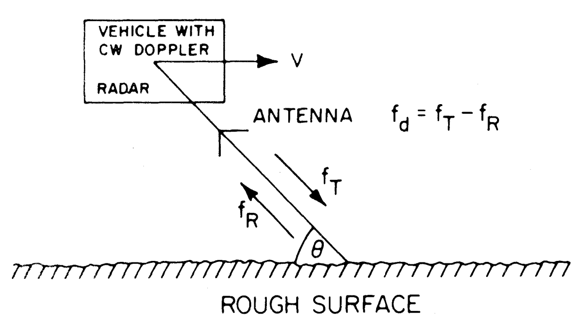

FIG. 1 Principle of operation of the Doppler velocity meter.

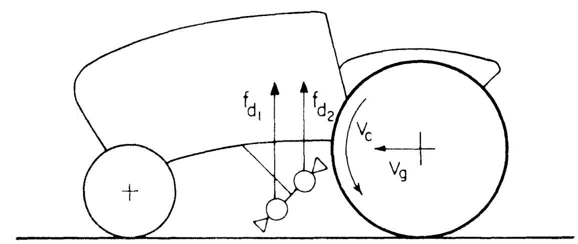

FIG. 2 Principle of operation of the Doppler radar slip monitor.

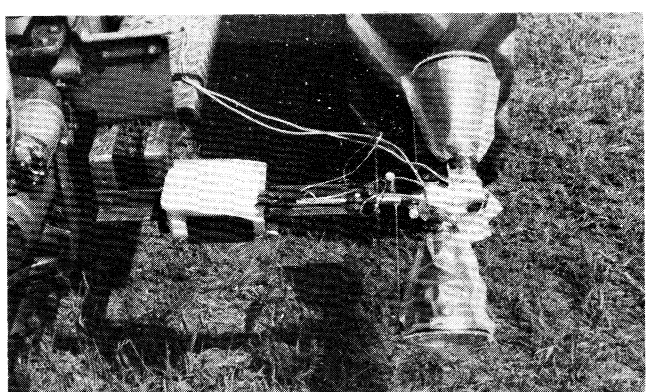

FIG. 3 Doppler radar modules installed in front of the tractor drive wheel for field test results.

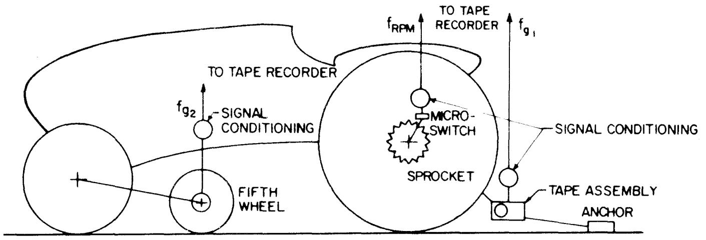

FIG. 4 Experimental arrangement of conventional slip monitoring system.

the Doppler modules as well as from the photoelectrical system, the magnetic pickup probe and the Microswitch assembly were recorded on three conventional portable, battery operated magnetic tape recorders for further processing in the laboratory.

All electrical signals obtained during the field tests were subsequently analyzed in the laboratory using different analog systems (Thansandote, 1976). Doppler signals were also analyzed using a PDP 11/40 minicomputer. The purpose of this analysis was to determine mean Doppler frequencies and to establish reference frequencies with which the results of the analysis by the analog technique could be compared.

The field tests were performed with the tractor without load and with a steady load. A second tractor was used as a variable load to produce slip up to 25 percent on the test tractor.

A second set of experiments was performed with a Versatile tractor model 900. Two configurations were evaluated. In the first configuration one Doppler radar module equipped with a conical horn antenna was attached near the center of the tractor on the underside of the chassis. The horn antenna was at an angle of 33 deg to the ground. A second indentical Doppler module was attached at a point on the top of the chassis with the antenna directed towards the top of the drive wheel tire. The viewing angle of the second Doppler module was selected experimentally to obtain a Doppler frequency equal to that from the ground speed module at no load on the tractor (assumed reference point-zero slip).

The conventional method of slip measurement in this configuration consisted of counting the revolutions of the drive wheel (monitored by the Doppler module) using a magnetic pick-up probe and a digital counter. The counter was triggered manually passing two markers on the ground separated by 60.96 m or 121.92 m (200 or 400 ft). Slip was determined as the difference between the number of pulses with a drawbar load and without a drawbar load normalized to the number of pulses without a drawbar load. The output signal form the Doppler slip monitor* was recorded by strip chart recorder for further analysis.

In the second configuration the ground speed was monitored by a Doppler radar module as in the first configuration while a signal proportional to the angular velocity of the drive line was obtained from a magnetic pick-up monitoring a sprocket attached to the drive line of the tractor. At no load the frequency of the signal obtained from the magnetic pick up was equal to the frequency of the signal from the ground speed Doppler radar.

In the first configuration the Doppler radar slip monitor measured the slip of one drive wheel, while in the second configuration the monitor measures the vehicle slip. The wheel slip and the vehicle slip could be different due to the action of the differential system of the tractor.

EXPERIMENTAL RESULTS AND DUSCUSSION

The no-load tests were performed with the test tractor driven on asphalt and gravel roads as well as on grass covered and on plowed fields. The purpose of these tests was to calibrate the fifth wheel with the measured tape system and to calibrate the ground Doppler radar against the fifth wheel. No-load tests also provided a zero slip reference point for calculations of slip.

The differences between the ground velocities of the tractor measured (grass-covered field)† by the fifth wheel assembly and those measured by the measuring tape system for tractor velocities ranging from 1 to 3 m/s were within ±1.5 percent (max. error) (Table 1). The ground viewing angle when this no-load experiment was performed on a grass-covered field was 48 deg.

The normalized difference between the ground velocity of the tractor measured by the fifth wheel assembly, V_W, and by the Doppler radar, V_g, is defined as

$$\delta = \frac{V_W - V_G}{V_W} \qquad [3]$$

The experimental results obtained in the second phase of this research are shown in Fig. 5 for different viewing angles of the Doppler radar. The differences are within 1 percent for viewing angles between 25 and 45 deg except for the asphalt road where the lower amplitude of the ground return signal caused errors in the frequency measuring system.

Doppler frequencies as determined by the analog system and calculated by the digital computer are summarized in Table 2. The difference between the two Doppler frequencies is within ±1 percent for the majority of cases. The experimental results summarized in Table 2 confirm that the analog system is reliable and provides sufficient accuracy of measurement of the Doppler frequency in complex spectra.

Load tests were conducted using the Microswitch and fifth wheel assemblies as a conventional method to measure the tractor-wheel slip. The mounting bracket was modified to allow the Doppler module assembly to be moved freely at 45 deg in respect to the ground and in between the tire and the ground. Two Doppler modules were fastened together and attached to the bracket. Several attempts were made to find a position for which the two Doppler frequencies were equal at no-load‡. Tractor-wheel slips measured by two Doppler radars and by the conventional method are summarized in Table 3. The experimental results show that although the slips measured by both methods differed considerably the technique of the Doppler radar slip monitor was feasible for practical purposes and, therefore, further tests in different configurations were performed.

*The monitor consisted of two frequency to voltage converters and a divider. The output signal of the monitor was proportional to the slip, according to the definition given by Equation [2].

†Although the fifth wheel assembly was used also on gravel road as well as on grass covered and on plowed fields, the comparison with the tape system was, due to the technical difficulties, limited to the paved road only.

‡Although it is possible to find an angular position for which the two frequencies are equal at no-load, the two frequencies remain equal only when tractor travels along a straight line. This indicated the difficulty in maintaining a reference point for a two radars configuration.

TABLE 1. GROUND SPEED OF THE TRACTOR MEASURED BY THE DOPPLER RADAR AND BY THE FIFTH WHEEL ASSEMBLY (NO-LEAD TEST, GRASS-COVERED FIELD).

Test no.	Velocity by fifth wheel, m/s	Velocity by Doppler radar, m/s	Difference,* percent
1	1.33	1.35	+1.5
2	1.92	1.93	+0.5
3	2.50	2.49	-0.4
4	2.89	2.85	-1.4
5	3.73	3.71	-0.5

*Normalized to the velocity determined by the fifth wheel assembly.

TABLE 2. COMPARISON OF THE DOPPLER FREQUENCY DETERMINED BY THE ANALOG SYSTEM AND CALCULATED BY THE DIGITAL COMPUTER.

	Doppler signal from the tire			Doppler signal from the ground		
Test no.	Analog system, Hz	Digital computer, Hz	Difference,* percent	Analog system, Hz	Digital computer, Hz	Difference,* percent
1	129.6	130.5	-0.7	107.2	108.0	-0.7
2	130.3	131.5	-0.9	109.1	110.1	-0.9
3	117.7	117.8	-0.1	84.8	84.1	+0.8
4	115.3	114.3	+0.9	86.3	86.3	0
5	105.2	105.5	-0.3			
6	143.8	144.8	-0.7	118.4	116.9	+1.3
7	119.9	120.2	-0.2	91.4	90.6	+0.9

*Normalized to the Doppler frequency calculated by a digital computer.

The slips of both tractor drive wheels are not the same and are not equal to the tractor slip unless both drive wheels are locked up together. One of the possible techniques for monitoring the tractor slip is to employ a tachometer to monitor the angular velocity of the power-take-off shaft (PTO) and to use only one Doppler radar to measure the true ground velocity. To experimentally check the feasibility of this technique, a method of monitoring slip with one Doppler radar and the microswitch assembly to monitor the angular velocity of the PTO was investigated. The calculated values of slip measured by this method are tabulated in Table 4 and are compared with the results obtained by two radars method and by the conventional method consisting of the Microswitch and the fifth wheel. The results show reasonable agreement, although the slip indicated by the Microswitch and the ground Doppler radar is consistently smaller than that measured by the conventional method. It is shown that monitoring slip with one Doppler radar and the Microswitch assembly (angular velocity meter) is feasible. Thus, if the magnetic pick-up probe is used as an angular velocity measuring device, the technique of monitoring slip with a magnetic pick-up and one Doppler radar is also feasible.

Encouraging results of the preliminary laboratory and field tests led to the design of a prototype of the Doppler radar slip monitor, shown schematically in Fig. 6. The slip monitor can operate with two Doppler radars or with one Doppler radar and angular velocity meter e.g. magnetic pick-up attached to the wheel or the drive line.

Field tests were performed in two configurations e.g. with two Doppler radars and with one Doppler radar and one angular velocity meter.

Fig. 7 shows the no-load results for the two radar configuration. Although the ground speed was almost

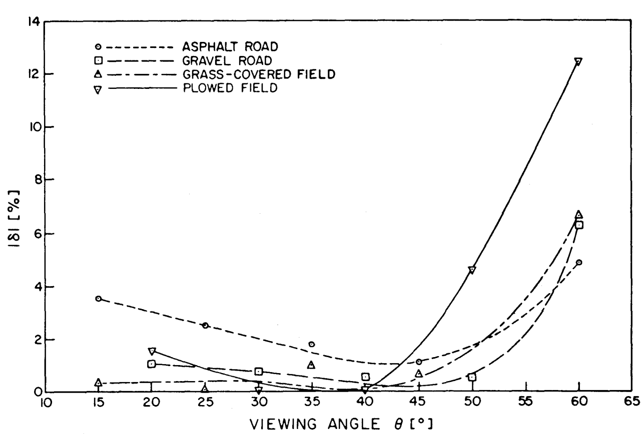

FIG. 5 |δ| as a function of viewing angle.

TABLE 3. COMPARISON OF THE SLIP MEASURED BY TWO DOPPLER RADARS AND BY A CONVENTIONAL METHOD*.

Test no.	Tractor speed, km/h	Doppler frequency, Hz		Slip, percent		Difference, percent
		Tire	Ground	Two Doppler radars	Conventional method*	
1	8.14	130.40	107.58	7.01	6.66	2
2	8.24	130.61	108.32	6.52	6.05	2
3	6.53	118.37	86.76	17.38	17.55	1
4	6.81	119.29	89.72	15.23	14.93	4
5	5.25	105.53	70.65	24.55	26.25	7
6	9.14	143.78	118.98	6.73	5.90	13
7	7.00	121.67	91.93	14.83	15.68	6
8	5.47	107.06	73.32	22.81	24.85	8

*Consisting of the microswitch and the fifth wheel assemblies.

constant the slip of the measured wheel varied considerably even on the asphalt road. Due to the difficulties in the calibration procedure e.g. in measuring slip at no-load further tests were performed in the second configuration. Some of the experimental results are shown in Figs. 8 and 9. The output from the slip monitor for a given run was averaged from the recordings by a planimeter and compared with a conventional method. The results of the tests performed on grass covered and on plowed fields are in satisfactory agreement for the majority of practical applications.

CONCLUSIONS

A new noncontact technique for monitoring tractor-wheel slip of agricultural tractors using two Doppler radars was developed. A conventional meter was set up and tested. The fifth wheel was calibrated using an original true ground speed measuring system. The difference maximum between the readings of this original system and the fifth wheel system was ±0.5 percent for tractor velocities from 4.8 to 9.6 km/h on

TABLE 4. COMPARISON OF THE SLIP MEASURED BY THE TWO DOPPLER RADARS, BY THE MICROSWITCH ASSEMBLY AND THE DOPPLER RADAR, AND BY THE CONVENTIONAL METHOD*.

	Slip, percent		
Test no.	Two Doppler radars	Microswitch and Doppler radar	Conventional method*
1	7.01	5.04	6.66
2	6.52	4.91	6.05
3	17.38	15.68	17.55
4	15.23	13.67	14.93
5	24.55	23.47	26.25
6	6.73	5.57	5.90
7	14.83	14.60	15.68
8	22.81	22.48	24.85

*Consisting of the microswitch and the fifth wheel.

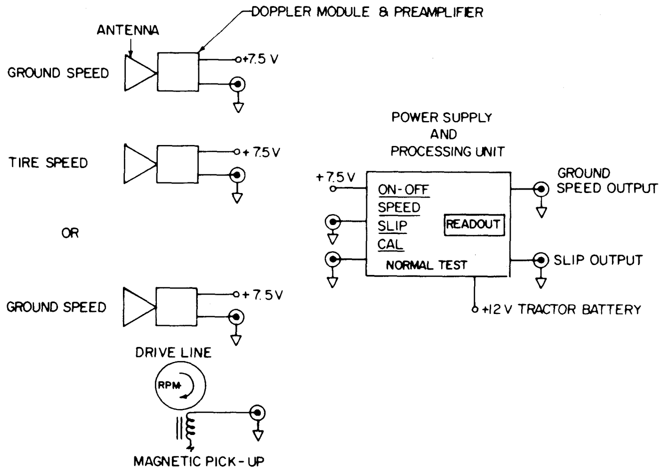

FIG. 6 Block diagram of the prototype of the Doppler radar slip monitor.

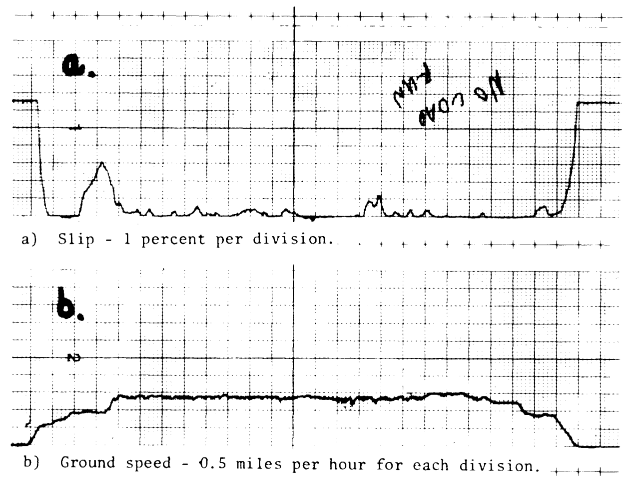

FIG. 7 Results of the field tests. Two Doppler radar modules, asphalt road, no load, chart speed 1 mm/s, time constant 3 s.

an asphalt surface.

The true ground velocity of the tractor was measured by a Doppler radar and the results were compared with the readings obtained from the fifth wheel. The differences between the velocities measured by both methods were below 1 percent for the viewing angles from 25 to 45 deg.

Finally, several tests were performed with a second tractor used as a variable load to produce slips up to 25 percent on the test tractor. The slip was measured simultaneously by two Doppler radars (tire and ground), one Doppler radar and an angular velocity meter on the drive wheel (sprocket and microswitch) and by a mechanical arrangement consisting of a fifth wheel and a tachometer. The results show good agreement, satisfactory for practical applications. The best results were obtained for one Doppler radar and an tachometer attached to the drive line.

The experimental results confirmed full technical feasibility of the Doppler radar slip monitor (DRSM). Recent advances in solid state technology provide relatively low-cost microwave Doppler radar packages which can be used in agricultural applications as tractor slip monitors. The DRSM seems feasible as a practical device for use on agricultural tractors.

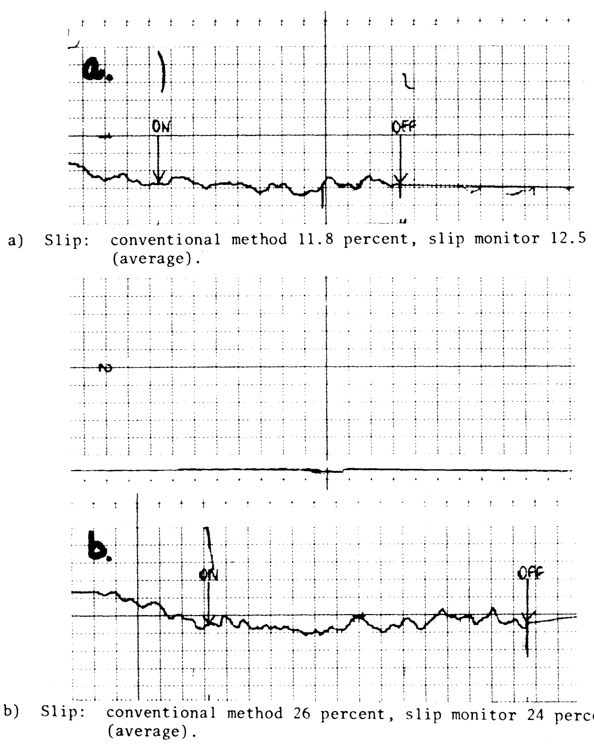

FIG. 8 Results of the field tests. The Doppler radar module and a magnetic pickup grass covered field, chart speed 1 mm/s, slip 1 percent/division, time constant 3 s. Arrows indicate the beginning and the end of the test runway.

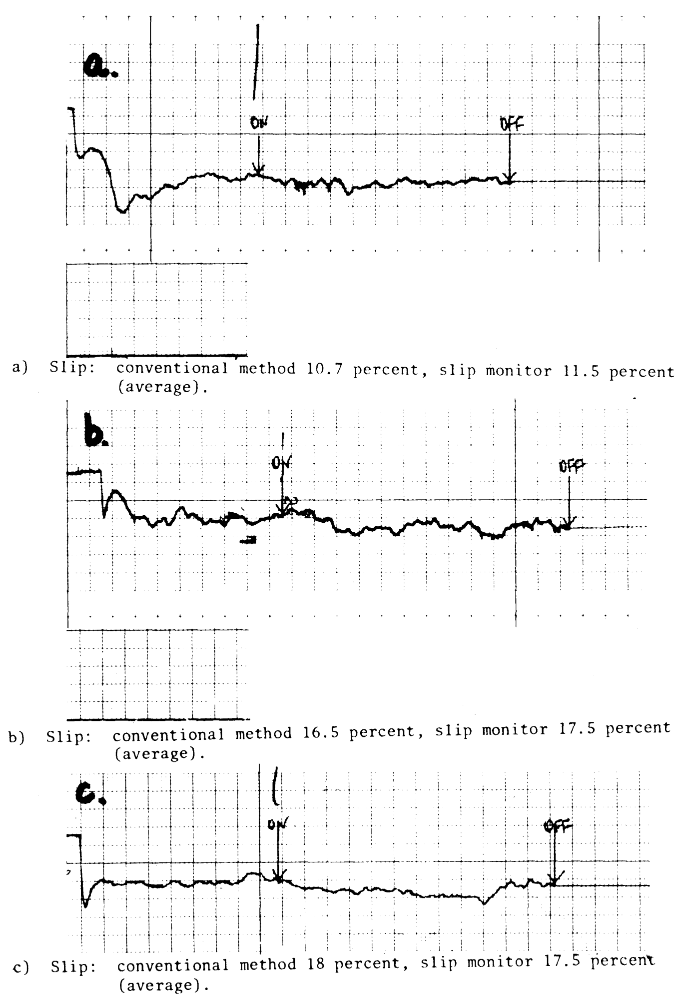

FIG. 9 Results of the field tests. One Doppler radar module and a magnetic pickup, plowed field, chart speed 1 mm/s, slip 1 percent/division, time constant 3 s. Arrows indicate the beginning and the end of the test runway.

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