A MOBILE TONE RANGE/RDF SYSTEM FOR TELEMETRY TRACKING OF SOUNDING ROCKETS

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Summary A simple and versatile tracking system is described, providing trajectory information for any rocket, balloon or airborne scientific device which employs telemetry.

The system is thought to serve as a back-up or a replacement for radar to provide the trajectory data of sounding rockets.

Two basic systems are comprised: the tone range system, providing the slant range information and the RDF system, providing angular data. Data reduction is handled by a small Computer.

Introduction Trajectory information of sounding rockets is required with high accuracy for

- missile trajectory surveillance
- data reduction of the scientific data
- recovery of payload.

Radar systems with sufficient accuracy are not always available on the ranges. Transport, installation and operation of mobile radar stations is extremely expensive, especially if a redundant system is required.

A simple, cheap and reliable method of obtaining trajectory information is given by tone ranging and angle of direction measurement by RF Interferometry. The necessary installations on board and ground site are relatively low in weight and easy to operate. Therefore this method is especially suitable for firings on ranges where practically no tracking equipment is available, as probably will be the case of launches for earth resource observations, solar eclipses etc.

Adding a small receiver to the rocket's payload, the slant range may be determinated by measuring the time delay of an electromagnetic wave radiated from the ground station and transponded by the rocket via telemetry. The vector of direction is measured by a RDF system, using the telemetry transmitter of the rocket as a target.

Slant range measurement The system described uses the "quasi-steady state" Doppler principle to obtain a range measurement. The RF-carrier (usually in the range 400 - 550 MHz) of the ground transmitter is modulated with a LF-signal (400 Hz - 250 kHz), the measuring frequency. For high resolution a high LF would be desirable. Practically the selection of the LF is always a compromise between the requested accuracy and the compatibility with the telemetry system. In case of a PCM system, for example, the clock frequency may be synchronized by the reference tone. So one has to live with the precision feasible with this frequency. Using an FM-subcarrier system all channels may be occupied by data of the experiments and only a TSC-frequency of 17 or 100 kHz may be free for use.

Let the ground site generated reference signal be denoted by

$$U_R = \hat{U}_R \cdot \sin\omega t$$

and the retransmitted signal, as received by the ground station

$$U_M = \hat{U}_M \cdot \sin\omega \left(t - \frac{2R}{c}\right) \tag{1}$$

with R = distance ground station/missile, c = velocity of light.

Comparing the phase of U_M against U_R one gets

$$\Delta\Phi = \frac{2\omega R}{c} \quad \text{resp.} \quad R = \frac{c \cdot \Delta\Phi}{2\omega} \tag{2}$$

Thus, range measurement is reduced to a phase shift or delay time measurement.

$\Delta\Phi$ becomes ambiguous at intervals of 2 π. In most cases it is not possible to introduce lower frequency tones for ambiguity removal. To get the absolute value of R, the number of 2 π-phase transitions η has to be registrated and added to the momentary value of $\Delta\Phi$:

$$R = K\,(\eta \cdot 2\,\pi + \Delta\Phi) \tag{3}$$

Fig. 1 shows a block diagram of the DFVLR ground station: transmitter, interface to the telemetry station and data reduction system.

The accuracy of the range measurement depends on the tone frequency, the precision of $\Delta\Phi$-determination, the phase delay stability of the slant range receiver, which is a function of the received RF power and the phase jitter introduced by noise.

A recent evaluation of a 17 kHz system gave an over-all performance of ±50 meters with a minimum power of -80 dBm at the input of the airborne tone receiver and the ground station telemetry receiver.

RDF-System Trajectory information is completed by the additional measurement of two direction cosines with a RF-interferometer, which has the great advantage that no additional board equipment is required.

The Interferometer system derives angular data by measuring the difference in electrical phase of the arriving RF-signal, radiated from the airborne system, at two ground antennas spaced 16 wavelength apart. By using two orthogonal base lines with two antennas positioned along every line, the azimuth and elevation angles can be derived from the electrical phase angles.

The phase difference measured between the signals received at each couple of antennas is expressed as

$$\Phi = 2\pi \frac{a - b}{\lambda} \tag{4}$$

a, b ... distance from the missile to the antennas
R ... distance from missile to the middle of the baseline
D ... distance of the antennas
λ ... carrier wavelength
δ ... angle between D and R

By using the cosine theorem it follows

$$a^2 - b^2 = 2\,DR\cos\delta$$

$$a - b = D\cos\delta\,\frac{2R}{a+b}$$

It R > D, a and b are very nearly equal to R and

$$a - b = D \cdot \cos\delta \tag{5}$$

By substitution of (4) into (5) the direction cosine can be determined directly from the phase difference

$$\cos\delta = \frac{a - b}{D} = \frac{\lambda}{2\pi D} = K \cdot \Phi$$

Fig. 2 is showing a block diagram of the RDF-equipment. The RF-signals of the 4 measuring antennas are multiplexed by a PIN-diode switch and converted by a normal single channel telemetry receiver to an IF of 400 Hz. After synchronous detection and filtering the phase comparison of each two signals is accomplished by time interval counters. The BCD-output of measured time difference, which is proportional to the difference in phase resp. the cosδ is directly connected to the computer input.

A doppler compensation is provided to avoid an additional error as a function of the vehicles speed.

By using only one receiver for all channels, there is no problem with phase delay instability as observed at multichannel systems. To reduce ambiguity (in case of signal drop outs) a coarse interferometer system with AZ2 baselines is available, too.

The precision of the system is tied to its resolution of phase. As the phase comparison is handled on 400 Hz IF with a 3 digit output (250 ms ≙ 2π rad) the resolution in direction cosine with 16 λ baselength is $2{,}5 \cdot 10^{-4}$. This corresponds an accuracy of the elevation angle of 0,014° near zenith and 0,032° at 20°.

The absolute precision is depending on many parameters, like stability of the transmitter's oscillator, accuracy of the RDF-antenna positioning, influence of ground etc. At low elevation angles the effects of multipath reflexion and tropospheric/ ionospheric refraction have to be considered, too. Test flights in comparison with a MPS-19 radar show that the tone range/RDF system is capable of providing an accurate trajectory with a maximum difference of 100 meters. Further comparison is expected to be done with a more accurate MPS-36 radar in near future.

Data reductions All phase -resp. time delay measurements have been done by HP 5327 B counters using a resolution of 3 decimal digits. The trajectories are calculated by an HP 2100 computer. The following quotations are used for calculation:

slant range $$R = \lambda \left(\eta + \frac{\Delta\tau}{T}\right) + Ro$$

- λ ... wavelength of the tone frequency
- T ... period of tone frequency
- Ro ... distance ground station - launcher
- η ... number of completed phase transitions
- Δτ ... time delay between reference and returned tone frequency

Direction

$$\cos\delta_x = \frac{\lambda}{D}\left(\eta_x + \frac{\Delta\tau_x}{T} + \frac{\tau_{Dx}}{T}\right)$$

$$\cos\delta_y = \frac{\lambda}{D}\left(\eta_y + \frac{\Delta\tau_y}{T} + \frac{\tau_{Dy}}{T}\right)$$

D	...	distance of antennas
T	...	period of the telemetry RF
η_x , η_y	...	number of completed phase transitions
τ_{DX} , τ_{DY}	...	constant time delay before launching
$\Delta\tau_x$, $\Delta\tau_y$	...	time delay measured during flight

Fig. 3 shows the flow chart for the incremental calculation of

R, resp. $\cos\delta_x$ and $\cos\delta_y$.

From these data the trajectory may be calculated in the carthesian coordinate system by the relations

$$X = \cos\delta_x \cdot R$$
$$Y = \cos\delta_y \cdot R$$
$$Z = \sqrt{1 - X^2 - Y^2}$$

In polar coordinates the angles of elevation and azimuth may be found directly without a Knowledge of R

$$\varepsilon = \arccos\sqrt{\cos^2\delta_x + \cos^2\delta_y}$$
$$\alpha = \arccos \cdot \frac{\cos\delta_y}{\cos\varepsilon}$$

For quicklook the slant range and the angles of elevation/azimuth are printed out every second.

Specification of the DFVLR Tone Ranging/RDF Ground Station Tone

Ranging:

VHF-transmitter	...	27 - 35 MHz, 100 W / AM/FM
UHF-transmitter	...	400 - 550 MHz, 100 W / AM/FM Stability 10^{-8}
tone frequency generator	...	frequency synthesizer, D-2 MHz adjustable in steps of 1/100 Hz, stability better 10^{-8}
transmitting antenna	...	low gain, omnidirectional
phase lock filters	...	on all IRIG PBW channels available (400 Hz - 165 KHz)

phase measurement resolution	...	HP 5327 B counter 3 digits/2π rad, depending on tone frequency

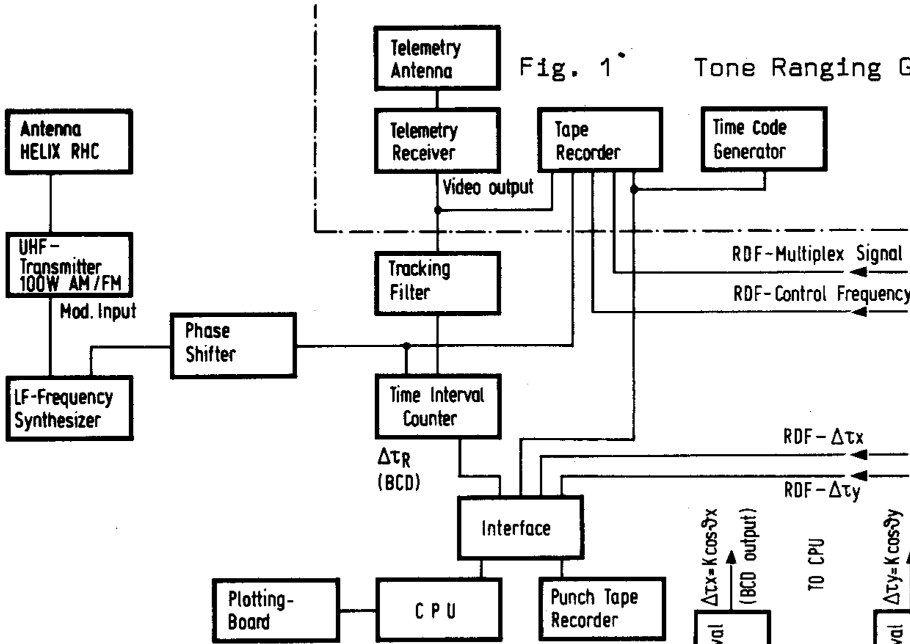
RDF:

frequency	...	210 - 260 MHz
antenna	...	crossed dipol, 3/8λ over a λ^2-reflector, diagram omnidirectional
accuracy of phase center	...	1°
baselength per axis	...	16 λ
accuracy of positioning	...	± 0.5 cm
multiplex unit	...	4 pole PIN diode switch
channel on-pos.	...	50 µs
channel off-pos.	...	150 µs
transient time	...	0,2 µs
demultiplex unit	...	4 pole electronic switch
channel on-pos.	...	50 µs
channel off-pos.	...	150 µs
transient time	...	1 µs
control pulse delay	...	0,5 - 10 µs adjustable
clock frequency	...	20 kHz, stab. 10^{-5}
channel cross-talk attenuation	...	35 dB
phase measurement	...	HP 5327 B counter
frequency	...	400 Hz
PLL-bandwidth	...	6 Hz
resolution of direction cosine	...	2,5 - 10^{-4} (3 digits/2π rad)
doppler compensation	...	± 2 kHz of RF
time base error	...	2 · 10-4 seconds

Data reduction:

Computer	...	HP 2100
punch tape recorder	...	HP 8100 A
digital recorder	...	HP 5055

Fig. 1 Tone Ranging Ground Station



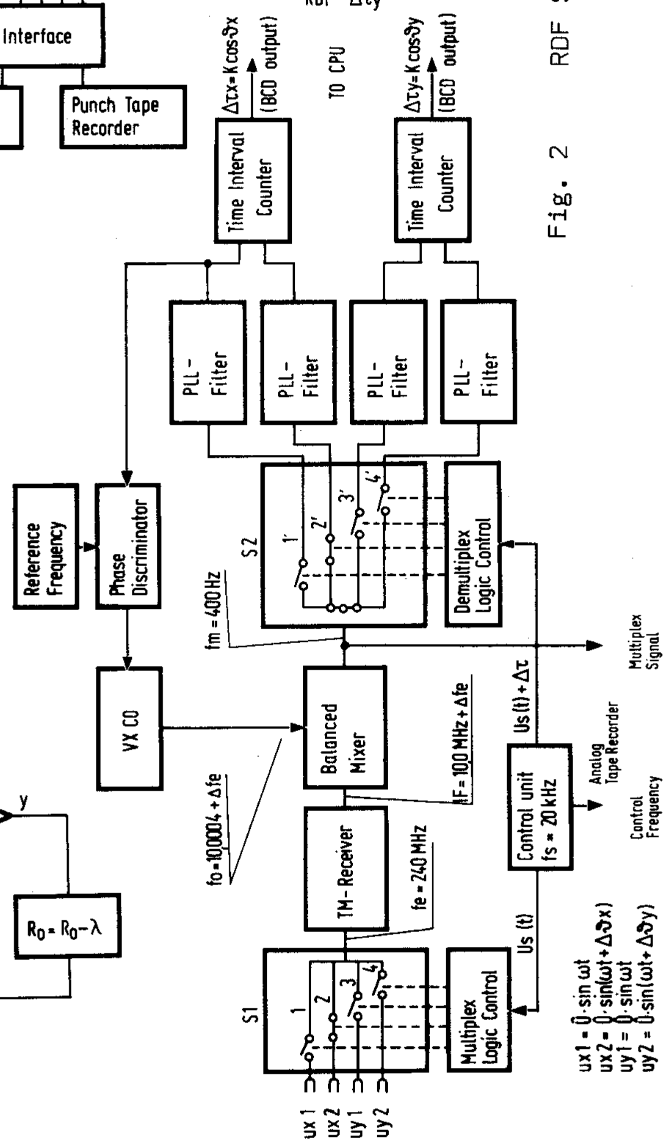


Fig. 2 RDF System

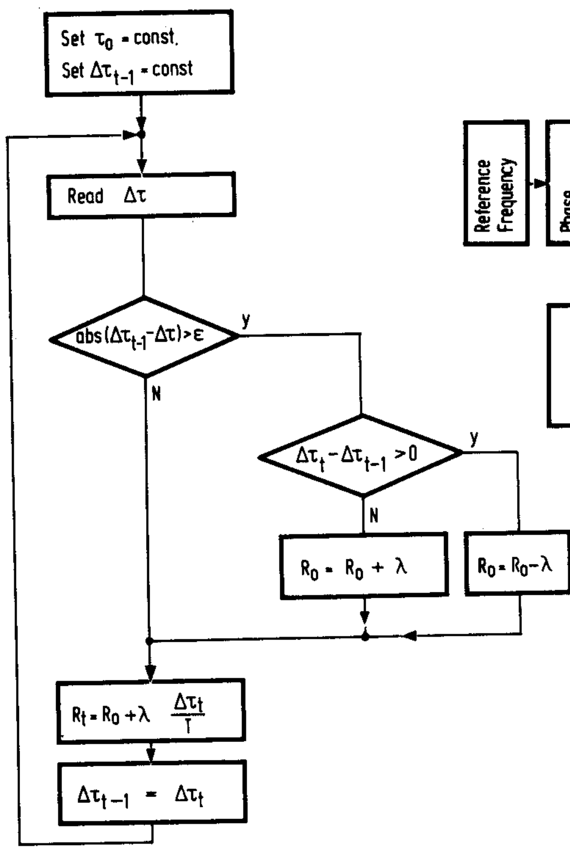


Fig. 3 Flow Chart of Incremental Phase Measurement