A NEW VHF-INTERFEROMETER WITH THREE STEERABLE HIGH-GAIN-ANTENNAS FOR SATELLITE-TRACKING

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Summary  The German-Central-Ground-Station near Weilheim, Bavaria, called Z-DBS, operates now on VHF-Telemetry and Telecommand. Its monopulse-autotrack-subsystem measures one way doppler datas and medium-precise (~0,25° RMS) direction angular (AZ,EL) datas. For precise orbital tracking the station will now be completed by a VHF-Interferometer with three steerable high-gain-antennas, using the angular information of the existing system for initial acquisition and ambiguity resolution. Such a system is applicable to track most near-earth-satellites in orbit without needing a global network even with a relatively low percentage of contact time because of its large angular- and distance-coverage from one topos. The interferometer, now under construction, will be ready for operation at the end of 1973. The present paper gives a brief description of the parameter requirements, the system itself and the methods used to overcome the very high technical difficulties. The total residual direction error is predicted not to exceed (10÷15)”, including nearby ground reflexions but excluding residual atmospheric propagation effects. High side-lobe-suppression-antennas with extremely stable phase characteristics as well as a 3-channel-piloting-receiver-system are used to make the antenna’s difference-phase errors small enough and to eliminate phase changes throughout long cables and receivers. A computer operates the whole system to a high degree of automacy and evaluates and smoothes the direction datas.

Introduction  In 1967 the author suggested the central-station-concept as a base for the german VHF ground system to be erected. This concept consists of a central station (called Z-DBS) equipped for VHF TM, TC in a first and precise Tracking in a further stage, located as close as possible to the german control center. This main station is assisted by a few small receiving stations, operating in an automatic mode, located stationer or semimobile dependent on the missions; the whole system is compatible for cooperation with other organisations (f.i. NASA). All events and station processes, during a given mission, which can be predicted to an allowable degree of tolerance for a given time intervall be operated automatically by programm or adaptive self-steering. Most of the mission commands are given through the central station, even in cases of retarded execution, if a reliable spacecraft tape-Telemetry system is available. The needed high degree of reliability on spacecraft and ground can be assumed. Though the
equipment investments per station are higher than for a normal station, one does not need a world wide system for many missions and the lower current operations-costs in personal and data transfer will justify such a system. The first stage was successful operated with “AZUR” and is now being prepared for “AEROS” and “SYMPHONIE”. Tracking datas have been supplied by NASA during the whole mission.

To complete the main station with the tracking function a VHF-radio-interferometer with steerable-high-gain-antennas has been designed and is now under construction. The central-station-concept requires for the tracking of responderless VHF-Beacon-Satellites a long range high coverage interferometer, therefore existing interferometers as Minitrack (NASA) or Diana (CNES, ESRO) are not to be considered. Steerable high-gain-antennas will provide better signal/noise ratio even at distances up to the moon and cover most of the upper topocentric hemisphere. In case of a low orbiting satellite, if only a few short contacts per day may be available, it is possible to determine the orbital parameters and their time-derivities for prediction and post flight use, if direction datas from a single or a few passes with high precision are measured from one station only. This has been shown by analysis of covariance-matrices for a low orbiting as well as for the transfer orbit of a geostationary satellite [1/11,12]. The importance to measure as precise as possible any available piece of orbit and to calculate the orbit as fast as possible is evident. The system is operable for post lounch phases and needs a-priori-information about the orbit for use of a differential-orbital-detemination computer-program.

The principal operation of an one-base-interferometer is illustrated in fig.1. A plane wave is assumed incident at an angle $\beta$ with respect to the base B. Antennas 1 and 2 are in our case steerable and pointed into the direction of the wave. The wavelength is designated with $\lambda$. Points 1 (2) represent the two phase centers of the antennas. As reference point the base-center is used. In case of a CW-signal it is possible to measure the phase-difference $\phi_1 - \phi_2$ instead of the time delay $\nu \Delta r$. If base B is large compared with $\lambda$, we have to solve for an ambiguity, that means for an integer $n$ of wavelength because phase-measurement is modulo 2$\pi$. If we know by measurements $\phi_1$, $\phi_2$, $\lambda$, the base B and its orientation, the direction cosine of $\beta$ may be calculated. Satellite’s position must than be on an rotation-hyper-boloid with focal points 1 and 2 and the range difference $\Delta r$. If the range is large with respect to B, we get a cone through the symmetrical reference point as an approximation. In case of a moving target, precise timing, correction for propagation and equipment delay’s and influence of averaging by bandwidth must be taken into account; furthermore the direction of incoming wave is not the true geometrical direction to the satellite beacon because of propagation phenomena in the atmosphere of the earth.
To find the complete direction of the incoming wave, we need a second base, usually orthogonal with equal length. The two bases are given direction to NS and EW. In case of steerable antennas it is less expensive to use only 3 antennas. It is reasonable to locate the 3 antennas as indicated in fig.2 and use as a reference point the center of hypotenuse.

**Ambiguity** “n” will be solved using the angular datas of the cooperating existing monopuls-autotrack-antenna-system. This high gain antenna-receiver system [1/15,16] is capable of measuring the direction of the incoming wave by autotrack mode with an error ± .2° down to 20° EL and less than ±.5° at 15°. The information (AZ,EL) is available in digital form for use in the station computers. The table in fig.1 shows the angular intervall $\Delta \beta$ per 360° phase shift versus the direction angle $\beta$ and the integer “n” [for the frequency range VHF 136 ÷ 138 MHz and a base length 126 m that corresponds to about 57 $\lambda$]. The available accuracy of angular datas delivered by the monopuls-antenna will be sufficient for ambiguity-solution [1/2,3,4]. Once the satellite-beacon-signal has been acquired and antennas have been pointed correctly, steering can be made either by slave-tracking through the autotrack-antenna or by self-steering by computer as long as ambiguity remains solved.

**The main subsystems** of the interferometer are: the 3-antenna system, the receiver-phase-measuring-system, the process-computer-system, consoles for handling and monitoring, and interfaces to the existing station, especially the autotrack-monopuls system, the timing equipment, which provides UT with an accuracy of .1 msec and modems to the data lines to the Control Center.

**The error situation** of such an interferometer has been carefully analysed [1/15,16,17]. Table in fig.1 shows, that near vertical incidence 1 degree change in phase difference corresponds to 10” in direction, whereas at low elevation we get 36”/degree phase. Because there are so many different reasons errors can be produced, we have a serious problem to hold each error (or its residual after correction of systematic errors) small enough.

**Antenna-system** First we have to discuss errors arising on the antenna-system, leading to erroneous phase difference measurement.

**Coherent multipath errors:** Different ground reflections will cause a phase error, though antennas are assumed with equal properties, but not with enough side lobe level suppression, or, at lower EL if the vertical antenna pattern does not provide enough signal suppression at deviation angles $\phi$ from beam-maximum approximately twice the EL. Since the interferometer must operate with full precision above 20° EL and should hold precision as good as possible down to 15°, the discussion of this question leads to a
trade off between realisable antenna properties with reasonable expenses, unequalness of ground reflection properties in amplitude and phase and realisable means to equalize that. Fig-3 shows definitions used for a simple calculation and the trade off results for a pair of antennas. The main signal is assumed to unity, the phase difference to be measured being eliminated. Under such condition each antenna produces on its output an additional, in general different \((\rho_1, \rho_2, \Psi_1, \Psi_2)\) multipath signal, which is added to the main signal vector. We ask for the phase-difference \(\Delta\phi\) between the two resulting signals, which must be a very small angle. Therefore \(\rho_1, \rho_2\) are both small values and the mean phase \(\Psi\) is undefined. The error-angle can be computed from fig.3(a).

\[
\tan(\Delta\phi) = \frac{2\rho\cos\Psi \sin \frac{\Delta\Psi}{2} + \Delta\rho\sin\Psi \cos \frac{\Delta\Psi}{2} + (\rho^2 - \frac{\Delta\rho^2}{4}) \sin\Delta\Psi}{1+2\rho\cos\Psi \cos \frac{\Delta\Psi}{2} - \Delta\rho\sin\Psi \sin \frac{\Delta\Psi}{2} + (\rho^2 - \frac{\Delta\rho^2}{4}) \cos\Delta\Psi}
\]

\[\text{using notations:} \quad \rho_1 = \rho + \frac{\Delta\rho}{2} \quad \Psi_1 = \Psi + \frac{\Delta\Psi}{2} \quad \Delta\rho = \rho_1 - \rho_2 << 1
\]

\[\rho_2 = \rho - \frac{\Delta\rho}{2} \quad \Psi_2 = \Psi - \frac{\Delta\Psi}{2} \quad \Delta\Psi = \Psi_1 - \Psi_2
\]

\[\Delta\phi = \phi_1 - \phi_2 = \frac{1 + \rho_1 \exp j \Psi_1}{1 + \frac{2}{\rho} \exp j \Psi_2}
\]

neglecting higher order terms \((\rho, \Delta\rho)\) in (1) we get a useful approximation for (1)

\[
\Delta\phi \sim 2\rho\cos\Psi \sin \frac{\Delta\Psi}{2} + \Delta\rho\sin\Psi \cos \frac{\Delta\Psi}{2}
\]

We eliminate now \(\Psi\), computing for a given set of \(\rho, \Delta\rho, \Delta\Psi\) the maximum value of \(\Delta\phi\) over \(\Psi\) in the usual way and replace \(\Delta\phi\) by \(\overline{\Delta\phi}\), and \(\cos\Psi\) \((\sin\Psi)\) by (3).

\[
(3) \quad \sin \frac{\Psi}{2} = \frac{\cos \frac{\Delta\Psi}{2}}{\sqrt{\sin^2 \frac{\Delta\Psi}{2} + \frac{\Delta\rho^2}{4}\cos^2 \frac{\Delta\Psi}{2}}}, \quad \cos \frac{\Psi}{2} = \frac{\sin \frac{\Delta\Psi}{2}}{\sqrt{\sin^2 \frac{\Delta\Psi}{2} + \frac{\Delta\rho^2}{4}\cos^2 \frac{\Delta\Psi}{2}}}
\]

\[
\left\{\frac{\Delta\phi}{2} = \left| \sqrt{\sin^2 \frac{\Delta\Psi}{2} + \frac{\Delta\rho^2}{4}\cos^2 \frac{\Delta\rho}{2}} \right| \right.
\]

which is presented in fig-3(b) for some possible values of \(\Delta\rho/2\rho\) between zero and .5.

For the three selected points 1,2,3 fig-3(c) illustrates the maximal influence of different multipath vectors \((\Delta\rho, \Delta\Psi)\) on \(\Delta\phi\) versus \(\rho\) in dB. Curve 1 does not need any equalness of ground reflections. To reach \(\Delta\phi < .1^\circ\) in the worst case \((\Delta\Psi = \pi)\) we need -60 dB suppression by antenna, which is not realizable. If we permit a Ap in the order of 20% of \(\rho\) and a \(\Delta\Psi\) up to 20° we get curve 3. Than -40 dB is a reasonable value for \(\rho\), which can be realised for the vertical diagram, as we will see later, on low elevation (15°). The
maximal phase-error on the antenna outputs, assuming equal antennas and pointing, will therefore be less than \(0.1^\circ\) under above conditions. A considerable part of this error will be eliminated by calibration by aircraft.

Ground reflections assuming physical ground conditions (ice, snow, water, dry loam ... ) have been calculated [1/36]. The result was, that without special means the conditions for \(\Delta \Psi\) and \(\Delta \rho\) can not be met. Therefore a system of 4 concentric metallic fences was proposed and will be mounted around each antenna. Modelling-measurements made at x-band [1/29] showed optimal fence-data and properties: height over ground (4m), depth underground (1m), the radii 16, 24, 32 and 44 m. The fences build-up regular and shifted n-corners with the upper line slightly saw-tooth shaped. Than \(\Delta \Psi\) can be predicted not to exceed 20° and \(\Delta \rho\) will remain lower than 20 % of \(\rho\). Because of the determined scattering rather than reflection phenomena, there will be an additional multipath propagation attenuation with respect to the specular case on \(\rho\) at low EL of about 6 to 30 dB. Furthermore-measurements have shown that irregularities of the ground surface within the critical regions and ground reflections coming from outside of the station at deviations from the horizontal by a few degree do not cause greater influence.

**Antennas** have been conceived and their predictable properties computed by H. Oettl, H. Goessl [1/27,2,3]. Only a brief description can be given here. Fig.4(a) illustrates the antenna-array-type above a reflector and the coordinate system, (b) the most important, computed and specified properties, including degradation-effects by tolerances in position of radiators and their amplitude resp. phase-illumination. The array consists of 32 crossed dipoles oriented at 45° versus the axis. Electrical steering is EL above AZ. Polarisation is right resp. left circular and can be switched from predictions, periodically or from the monopulse-autotrack-system which is able to determine the degree of polarisation incoming. Construction is extremely stable in a static as well as dynamic sense. To provide very high side-lobe-suppression, illumination is made by Dolph-Tschebyshev-tapering the amplitudes with equal phases. Cabling is made very stable and protected against temperature and humidity effects. Curves shown in fig.4(b) are taken from computed amplitude-patterns versus \(\varphi\) for different cuts in \(\Psi\). There are shown the -3 and -20 dB curves of the main lobe, the angular position (\(\varphi, \Psi\)) of the 1. side lobe and of equal-level-points on the main lobe. Due to the right scale the worst-case side-lobe-suppression depending on \(\Psi\) is shown. The back side radiation pattern (\(\Psi > 90^\circ\)) is below -40 dB. Measurements on existing antennas and comparison with calculations showed good agreement so we are shure that these values will hold. From fig.4(b) it is seen, that all requirements outlined with respect to multipath interference at low EL will be satisfied. Vertical pattern will look at 15° EL to the critical ground zone with a relative weighting below -45 dB (\(\Psi = 90^\circ\)).
**Phase characteristic-error:**  Fig-5 shows the requirements specified with respect to the phase characteristic of the antenna. Values are taken from computations and phase measurements carried out on existing antennas. Shown curves represent the maximum expectable phase-deviations as a result from the tolerances indicated in fig.4 and distributed in such a way, that unsymmetrical characteristics occur. The result may be interpreted: If all antennas are pointed to the incoming wave accurate and equal, phase error may be neglected because it will be much smaller than \(0.1^\circ\). The table indicates 3 pattern-deviation-ranges for operation with their corresponding phase-errors which can be expected. A large part of this error is a systematical one, because by calibrating the interferometer with an RF-beacon on an airplane most of this error can be corrected. In some cases, if a satellite passes near the zenit over the station at low altitudes, the EL/AZ-steering cannot follow precise and will lose the satellite because of limited azimutal angular-speed. In such case angle-lead-steering with an average azimut has been successfully practised with deviation in \(\psi\) up to 4 degree. The uncorrected error is than expected to rise up to \(0.4\) degree phase. From fig.4 it is also seen that coherent pointing of the three antennas must be held better than \(0.05^\circ\) because otherwise additional phase pattern errors would occur due to the unavoidable distance \(p\) (fig-5) between EL-axis and reflector. This type of error is related to a slight change of the base B and discussed later [1/28].

**Error by scattering from antennas:** As an outcome this type of error is completely negligible at EL down to \(15^\circ\). To get an estimation, fig.6 shows the angular-geometry between antennas (i) to (k) and the relations between the pattern-coordinates \(\psi, \Psi\) and the EL/AZ distances, shown for the two cases \(15^\circ\) and \(20^\circ\) EL. Each antenna will scatter some power to the other and contribute to a phase-difference-error. Estimating the worst case, we use Krauss’ theorem about equalness of absorption- and scattering-cross-section of a lossless, matched antenna. The ratio of the power scattered from antenna k to i to the received incident power at i (taken to unity), and vice versa, gives the multipath vector \(p\) on each antenna, both being assumed in opposite direction. \(g\) represents the relative pattern function and \(\sigma\) a relative scattering function.

\[
\rho^2 < 2 \cdot G_0 \cdot g(k+i) \cdot \sigma(i+k) \cdot \left(\frac{\lambda}{4\pi B}\right)^2 \Rightarrow -89\ dB \quad \text{with}
\]

\[
G_0 \approx 22\ dB; \ g(k+i) < -23\ dB, \ \sigma(i+k) < -40\ dB, \ \left(\frac{\lambda}{4\pi B}\right)^2 \approx -51\ dB
\]

A value of -70 dB (curve 1 in fig.2) would be sufficient for complete neglection.

**Base-errors** A basic error equation one gets by differentiating the relation between \(\cos\beta, \lambda, B\) and \(\Delta\phi\) in fig.1. We get for each base
The relative error in propagation velocity \( v \) of EM-waves immediately around the interferometer can easily be held less than \( 10^{-6} \), measuring the average refractive index near ground directly, or via humidity, temperature and pressure, using well-known formulas. The relative error in frequency can also be held less \( 10^{-6} \), because the carrier frequency is measured by the equipment itself to about \( 1 \ldots 1 \text{ Hz} \) as a function of time including doppler effects. So, if base errors are small enough and their residuals under control \( (< 5 \cdot 10^{-6}) \) the phase-error \( d(\Delta \phi) \) in (6), which is not possible to make if such smaller will remain the dominant error. That means, each antenna’s geometrical phase-center must remain within an error-sphere with radius \( 0.6 \text{ mm} \) fixed on the endpoint of themoving arm \( p \) from axis-cross-point (fig.2,7), including relative steering errors (fig. 7(c)). To provide these conditions, on the bottom of each antenna a measurement-foundation-block is used. The axis-cross-over-point in \( 10 \text{ m} \) height is fed down vertical with optical means, height is measured to \( 0.1 \text{ mm} \) with invar-steel band using dials-gauge. Base (B) direction and distance is triangulated through the underground pipes (S) using “Tellurometer”- and hydrostatic balance methods. Last not least the steering error is held down to \( 0.05^\circ \) in any direction, though from its own contribution alone we could admit \( 0.5^\circ \), as we can prove from the formula in fig.7(b) with \( \theta = 4^\circ \), \( \rho = 1.158 \lambda \), and \( \Delta B = 0.5 \text{ mm} \). Base error is varying very slowly and can be corrected as a systematical error from measurements, if the values deviate too much from the values used as nominal during interferometer calibration. The residual should be small enough including statistical steering errors.

**Parallax-error** This error depends on the distance \( (R) \) to a target. It is much larger than in the case of crossed-base-symmetrical-interferometer li minitrack with 4 antennas. While in the later case the error in direction-cosine is approximately given by

\[
\cos \beta(R) \approx \cos \beta(\infty) \cdot \left[ 1 - \frac{1}{2} \left( \frac{B}{2R} \right)^2 \right]
\]

and is negligible beyond 20 km, in our case, this error must be handled as a systematic one and corrected using an a-priori-knowledge about the topocentric distance to the spacecraft up to 3000 km. The error has been calculated [1/18,20] as a function of distance and direction, the result shown in fig.8. A first approximation which can be used beyond 100 km is

\[
\Delta(\cos \beta) \approx \frac{B}{2R} \cdot \cos^2(\theta L) \frac{\sin^2(AZ)}{2} \quad \text{or} \quad \left\{ \begin{array}{l} l - l_o = \Delta l \\ m - m_o = \Delta m \end{array} \right\} \approx p l_o m_o
\]

which is presented in normalized form versus AZ in fig.8. The accurate correction-formula is given by the following expression.
Iteration of (9) on a computer converges very fast, using measured uncorrected values $l_0$ and $m_0$ as initial estimates under the roots. At normal satellite distances ($R > 250$ km), the approximation (8) can be used, for calibration by aircraft ($R = 10$ km) formula (9) or a quadratic approximation should be used. At medium satellite distances an a-priori-knowledge of $R$ with a 10% accuracy will be sufficient, to get the residual error after correction small enough to be neglected ($10^{-6}$). For calibration, distance to aircraft must be measured with an accuracy of 0.1%. 

Receiver-Phase-Measuring-System  A special feature of the described interferometer will be the “pilot”-controlled-3-channel receiver, the operation principle of which is illustrated in fig.9. Only essential parts are indicated. A pilot-receiver-channel begins with the coupling of a pilot-signal immediately on the antenna-array-output and ends with the selection of the pilot from the signal carrier. It contains the antenna unit with the directional coupler, a bandpass-filter, a wide band 30 dB-gain-low-noise-preamplifier, then the long-cable-way through the rotary-joints for EL and AZ to the remote main receiver. The receiver is a triple-heterodyne type the 1. LO being part of the carrier PLL, and the other LO’s derived from synthesizer references (RS). The last IF is chosen to 10 KHz. All references are coherent with universal time (UT). Though all 3 channels underly equal environmental conditions and are designed equal and very stable, it is not possible to equalize the phase shifts ($\epsilon$) precise enough. Therefore the used pilot-system provides the control of the 1. LO to eliminate different phaseshifts of channel $k$ relative to the central channel (1) and a properly processed pilot-signal is controlled to a well defined phase relation with respect to the received signal of the central channel. As central channel the channel from the common antenna of the two bases (1) is chosen, because following the doppler effect at this antenna, the differential doppler effect is low enough. Following the phase-indications on the fig.9, we get on the output a phase difference $\theta_k - \theta_1$ equal to the signal-phase difference on the input $\sigma_k - \sigma_1$

\[
(10) \quad \theta_k - \theta_1 = \sigma_k - (\phi_k - \epsilon_k) - (\sigma_1 - \phi_1 + \epsilon_1) \Rightarrow (\sigma_k - \sigma_1)
\]

The 1. LO phase $\phi_1$ of the VCXO will be controlled by the carrier-PLL to drive the phase difference to the 10 KHz reference to zero. Then $(\phi_k - \epsilon_k)$ should be treated in such a way to equal it with $\sigma_1$. From the pilot-reference-PLL we get $(\theta_k - \epsilon_k)$ equal to $p_k$. Now we have to equal the electrical lengths of the pilot-ways $\beta_i = \beta_k$, or if there is a small
difference $\delta_k$, we have to measure it, as explained later. We replace $p_k$ by $(p_1 + \delta_k)$. However $p_1$ will be controlled equal to $\sigma_1$, using the pilot-PLL of channel 1. For the oscillator phase $\phi_k$ we get the condition

$$\phi_k \Rightarrow \phi_1 + (\epsilon_k - \epsilon_1) + \delta_{k1} \quad (k = 2, 3)$$

using the two pilot-control conditions simultaneously.

$$p_k - p_1 \Rightarrow (\phi_k - \phi_1) - (\epsilon_k - \epsilon_1) \Rightarrow \delta_{k1}, \text{ or zero.}$$

Therefore in the k-channel a phase shifter adds to the 1.LO phase $\phi_1$ the phase $(\epsilon_k - \epsilon_1)$ as a result of the pilot-PLL of it.

To provide equal or known (slight different) pilot phases at the 3 coupler’s, the ways $\beta_1$, $\beta_k$ must be controlled after adjustment. This is called an ELM- (electrical length measurement)-system and represents a CW-radar, which uses a separate carrier a few MHz away from the 136 MHz band. This system can either be made to compensate for slight phase differences by controlled phase-shifters or to measure $\beta_k - \beta_1 = \delta_k$, and use this information for phase-correction in the computer.

The choice of the pilot signal presupposes some requirements. First the pilot spectrum must not contain the signal carrier. This can be done by modulating the reference with a PN-code in such a way, that only two sidebands without carrier occur. The pilot phase can then be regenerated by correlating the 3rd IF-PN-pilot against its reference-replica. It is evident, that the channels phase-characteristic versus frequency at any condition must be linear or point-symmetrical otherwise phaseshifts $c$ for carrier and pilot are not equal. The pilot-directional coupler at the input and the PLL-filters to select the signal carrier at each channel-output are to make precise equal; the pilot is AGC-controlled to a level at input only slightly higher than the signal [1/31,32].

The phase differences on the output are measured by start-stop-counting phasemeters (PHM) with a sufficient high clock frequency (75 MHz) to provide at 10 KHz an accuracy .05°.

The doppler frequency of the satellite signal, which is eliminated by the carrier-PLL at the output, is taken from the VCXO, the bias-frequency being known, counted and fed to the computer. There is a difference-doppler effect due to the slightly different relativ-velocities of the target at the 3 antennas. This effect has been treated and is negligible. PLL-band-widths must be chosen carefully in agreement with the predicted range and range-rate and to miniMiBe noise errors. The total phase-error of the receiver-system is specified and can be expected not to exceed .2° phase per base excluded signal to noise-errors. Phase countings are transferred with 10 Hz sample rates to the computer.
Process-Computer  Its main datas are 16 K 24 bits/word 1 usec cycle. The most important functions which give the interferometer a high degree of automacy are: [2]

– The on-line processing of all datas measured by the interferometer, together with correctives, to smoothed, noise filtered, corrected direction cosines, precise timing and blockwise transfer in compatible format to the orbital computer in the GCC.

– The acquisition processing with ambiguity-solution using the angular information abilities of the existing station.

– The regeneration of AZ/EL-datas from direction-cosines using ambiguity solution and remaining unique results in “on-line” for interferometer-auto-track-mode.

– The parameter setting on the basis of predictions, status control of the whole equipment, a protocoll print-out after each passage of a spacecraft. - Short-loop and long-loop tests and providing the test-datas.

Calibration of the interferometer will be done by airplane in a similar way as for “Minitrack and Diana”. The aim is the elimination of all reproducible systematic errors. VHF-calibration datas will be compared with simultaneously taken optical flash-light datas photographed toward the clear night-sky. Range is measured by radar. A problem will be to provide a very stable phase-center of the VHF-antenna, mounted on the bottom of the aircraft with the flash-light in its center. Within an aspect-angle of at least 60° with respect to the vertical, the phase center should be stable in a sense of 10 - 20 cm, to provide the needed calibration accuracy of only a few seconds of arc (1/19).

Conclusion  To put this new VHF-interferometer with steerable high-gain-antennas successful in operation, many technical problems have arisen and satisfactory solutions have been found. If attention is paid to all details, an operable interferometer with a total error not to exceed 10 - 15" should be the result. The relative large propagation-error due to ionosphere at VHF must be mentioned. Special attention has been paid to the development of a databank to get the best possible systematic error-correction from actual profile measurements. Only a very brief review of the work done could be given, the results of the operational interferometer will be presented later.

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Most of the indicated literature is contained in [1] under the second number
[1] W. Fogy; DFVLR int.rep. IB-34/71

![Fig 1 PRINCIP of ONE - BASE INTERFEROMETER](image1)

![Fig 2 INTERFEROMETER LOCATION - LAYOUT](image2)
Fig 3  MULTIPATH ERROR INFLUENCE

\[
\hat{\Delta \phi} \approx \sqrt{\sin^2 \frac{\Delta \psi}{2} + \left(\frac{\Delta \rho}{2 \rho}\right)^2 \cos^2 \frac{\Delta \psi}{2}}
\]

Fig 4  ANTENNA - MAIN PROPERTIES

ARRAY-ANTENNA

tapered D-TCHEBYSHEV
COORDINATES

GAIN \( G_0 = 22 \text{dB} \)

EL/AZ

\( \frac{\pi}{4} \)

\( \psi \)

\( \phi \)

TOLERANCES: \( \Delta \phi \pm 3^\circ \)

Ampl. \( \pm 5\% \)

position: \( 10^{-3} \lambda \)
Fig 5 PHASE - CHARACTERISTICS

Fig 6 ESTIMATED ANTENNA - SIGNAL - SCATTERING
  a) GEOMETRIC  b) PATTERN - LEVEL

Fig 7 BASE - ERRORS
Fig 8 PARALLAX - ERROR APPROXIMATION

Fig 9 RECEIVER - PHASE - MEASURING SYSTEM. PRINCIP of OPERATION

Fig 10 CENTRALSTATION - WEILHEIM/BAVARIA. LAY-OUT