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The influence of atmospheric loading on VLBI-experiments

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Abstract. Air pressure lows and highs with periods of some days and seasonal variations of mean air pressure can be regarded as loading functions on the Earth's surface. They result in quasi-periodic surface deformations. The influence of such displacements on the results and the accuracy of VLBI experiments (Very Long Baseline Interferometry) is investigated by simulation calculations for the transatlantic Effelsberg-Haystack baseline. Different models for the time dependence of air-pressure-induced station displacements are considered. It is shown that today's standard VLBI data analysis, including model parameters for clock- and atmospheric-refraction effects, is not able to correct the measurements for atmospheric loading effects. It leads to erroneous baseline vectors. Hence, for every geodetic VLBI experiment, the amount by which (1) the local air pressure at the station and (2) the mean air pressure in a surrounding area of 2,000 km radius has changed during the experiment should be tested. These two values give an estimate of the resulting vertical displacements by the use of a regression formula. The corresponding delay-time corrections have to be applied to the VLBI data. Most of the radiotelescopes participating in geodetic VLBI experiments are situated in regions with small seasonal variations of the station position. However, an increasing VLBI accuracy and an expanded and denser VLBI network will also require the consideration of seasonal displacements.

Key words: Geodynamics – Atmospheric loading – Global deformation – Global positioning – VLBI

Introduction

The improvement of geodetic space methods with regard to instrumentation and processing has reached centimetre precision for the determination of changes of global baselines (Lundquist, 1984). This enables us to investigate geodynamical processes which are associated with point displacements on the Earth's surface. For example, the determination of continental drift rates of some centimetres per year may become possible in the near future via Very Long Baseline Interferometry (VLBI), Lunar or Satellite Laser Ranging (LLR, SLR) or even by the differential application of the Global Positioning System (GPS). Deformations of the Earth's surface, however, are not only of endogenic, i.e. tectonic, origin. The Earth's surface is affected by a lot of exogenic deformation effects of partly periodic, partly quasi- and non-periodic character. The most prominent example of the former are the body tides and ocean loading tides. An example of not strictly periodic deformations are those effects which are caused by the atmosphere: by air pressure lows and highs (deviations from the 1,013-mbar atmospheric mean), snow coverage during winter or anomalous sea-level changes caused by storms.

Since geodetic methods have come close to the accuracy which is necessary for large-scale tectonic investigations, the question of data correction corresponding to exogenic displacements has become more important.

This paper deals with errors of VLBI data analysis which are introduced by air-pressure-induced, large-scale surface deformations. Their magnitude can exceed the approached VLBI accuracy. The next section gives a short summary of theoretical estimations of air-pressure-induced station displacements, followed by a section which deals with the corresponding correction of the VLBI observables. In the subsequest section, the influence of air-pressure-induced station displacements is simulated for the transatlantic Effelsberg-Haystack baseline. Different models for the time dependence of the displacements are assumed. The final section contains a proposal for the treatment of such station displacements for the interpretation of VLBI measurements.

Air-Pressure-Induced Displacements at the Earth's surface

Air pressure lows and highs (cyclones and anticyclones) can be regarded as time-dependent loading on the Earth's surface. According to their geometry they generate large-scale deformation fields with some hundred up to some thousand kilometres wavelength. Due to the velocity of the passing (anti-)cyclones, the periods of the loading function are between a few days and some weeks. Such air pressure anomalies can cause vertical displacements in the centimetre range and horizontal displacements in the millimetre range (Trubytsin and

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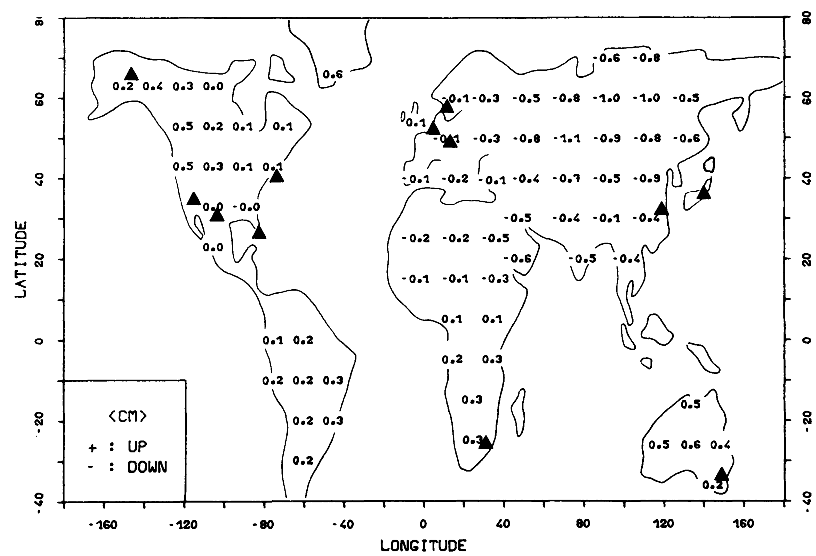

Fig. 1. Vertical displacements due to seasonal changes in the global air pressure distribution: mean deviation "January minus July" (from Rabbel and Zschau, 1985). Positions of radiotelescopes participating in geodetic VLBI experiments are indicated by *triangles*

Makalkin, 1976; Rabbel and Zschau, 1985). The isobars of many (anti-)cyclones are close to being circular and can be roughly approximated by bell-shaped pressure distributions. Such an (anti-)cyclone, of typically 2,000-km diameter and extreme maximum pressure of ± 60 mbar (see e.g. Faust, 1968) in its centre (deviation from atmospheric mean), yields ∓ 25 mm vertical and ± 2.5 mm horizontal displacements as a maximum estimation.

Discontinuities of the pressure distribution, e.g. which can be generated at coastlines due to the static response of the sea (inverted barometer effect), will modify these values but do not change their order of magnitude. Seasonal air pressure variations with a quasi-period of 1 year can be estimated from the mean values in January and July. They are about 10 mm double amplitude for the vertical displacements (Fig. 1) and 1 mm double amplitude for the horizontal displacements. Extreme values are to be found in Siberia, Greenland and the Antarctic (Stolz and Larden, 1979; Rabbel and Zschau, 1985).

The standard method for the estimation of loading effects is the method of Green's functions: the (visco-) elastic equation of motion is integrated numerically for a radially symmetric Earth model with a surface point load as exciting function. The resulting deformation response, expressed in terms of loading Love numbers and Legendre polynomials, are the so-called Green's functions. They are convolved with the desired arbitrary surface load distribution in order to obtain the total deformation (e.g. see Longman, 1962; Farrell, 1972; Zschau, 1979).

Vertical displacements are not only determined by the local pressure but also by the long-wavelength terms of the load distribution. Therefore, the somewhat laborious method of the Green's functions cannot be replaced by a simple regression between local air pressure and vertical displacement. However, under static conditions it is possible to estimate the vertical displacement by a regression approximation introducing two regression coefficients, namely for the short- and the long-wave-length loading (Rabbel and Zschau, 1985):

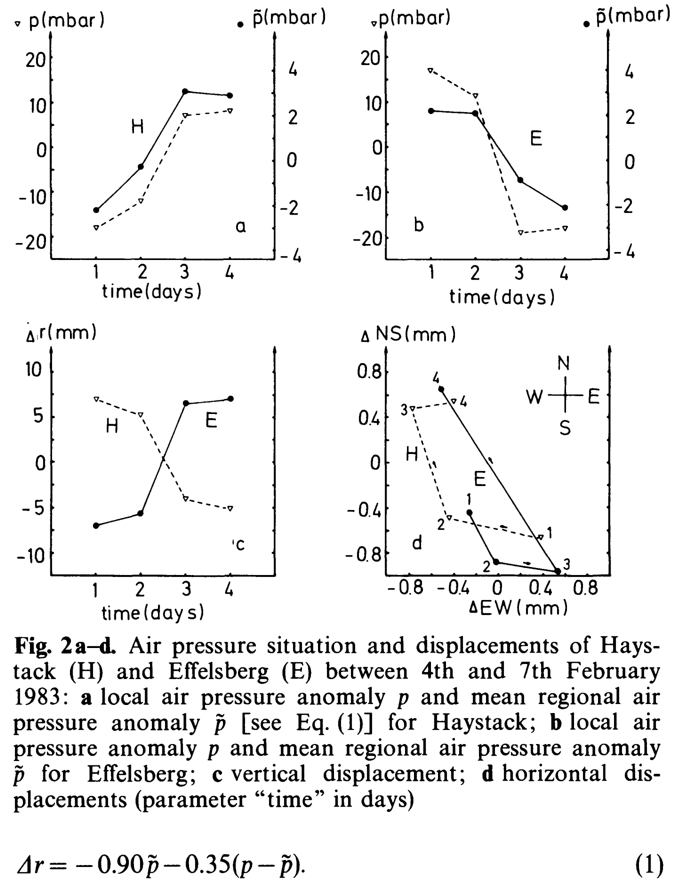

Fig. 2a–d. Air pressure situation and displacements of Haystack (H) and Effelsberg (E) between 4th and 7th February 1983: **a** local air pressure anomaly p and mean regional air pressure anomaly $\tilde{p}$ [see Eq. (1)] for Haystack; **b** local air pressure anomaly p and mean regional air pressure anomaly $\tilde{p}$ for Effelsberg; **c** vertical displacement; **d** horizontal displacements (parameter "time" in days)

$$\Delta r = -0.90\tilde{p} - 0.35(p - \tilde{p}). \qquad (1)$$

Here Δr(mm) is the vertical displacement, p(mbar) is the local air pressure anomaly at the station position and $\tilde{p}$(mbar) is the mean value of the pressure anomaly within a circular region of 2,000-km radius. $\tilde{p}$ denotes the long-wavelength component of the pressure variation. For ocean areas the pressure contribution to $\tilde{p}$ has to be set to zero due to the static response of the water masses. Equation (1) allows to estimate seasonal displacements with an error of less than 1 mm. Figure 2 gives an example of the variation of site positions within four succeeding days. The local and mean regional air pressure anomaly p, $\tilde{p}$ and the resulting vertical and horizontal displacements Δr, ΔNS, ΔEW are shown for the VLBI stations Effelsberg (W. Germany) and Haystack (Mass., USA) between 4th and 7th February 1983. In this time interval the variation of the vertical displacement exceeded the 1-cm limit and the maximum horizontal movements were about 1 mm. The given displacement values correspond to the Gutenberg-Bullen *A* earth model as tabulated in Alterman et al. (1961).

Correction of VLBI observables for atmospheric loading

The basic VLBI equation for the geometric delay τ is

$$\tau = \frac{-\vec{\mathbf{b}} \cdot \vec{\mathbf{k}}}{c} \tag{2}$$

τ consists of the scalar product of the baseline vector $\vec{\mathbf{b}}$ and the unit vector in radio source direction $\vec{\mathbf{k}}$, divided by the velocity of light c. Equation (2) can be used to compute the delay corrections τ_{ld} due to displacements $\Delta\vec{\mathbf{r}}^i_{\mathrm{ld}} (i=1,2)$ of two VLBI stations which may be caused by atmospheric loading. Referring to Fig. 3, we define

$$\vec{\mathbf{b}}_0(t) = \vec{\mathbf{r}}^2(t) - \vec{\mathbf{r}}^1(t) \tag{3a}$$

and

$$\vec{\mathbf{b}}_{\mathrm{ld}}(t) = [\vec{\mathbf{r}}^2(t) + \Delta\vec{\mathbf{r}}^2_{\mathrm{ld}}(t)] - [\mathbf{r}^1(t) + \Delta\mathbf{r}^1_{\mathrm{ld}}(t)] \tag{3b}$$

and

$$\Delta\vec{\mathbf{b}}_{\mathrm{ld}}(t) = \vec{\mathbf{b}}_{\mathrm{ld}}(t) - \vec{\mathbf{b}}_0(t). \tag{3c}$$

$\vec{\mathbf{b}}_0(t)$ is the baseline vector at time t under reference conditions (e.g. for a constant global air pressure), $\vec{\mathbf{b}}_{\mathrm{ld}}(t)$ is the baseline vector after consideration of the load-induced displacements $\Delta\vec{\mathbf{r}}^i_{\mathrm{ld}}$ of the VLBI stations. The displacement vectors $\Delta\vec{\mathbf{r}}^i_{\mathrm{ld}}$ of the two stations may be expressed in vertical and horizontal components. Inserting the difference vector $\Delta\vec{\mathbf{b}}_{\mathrm{ld}}(t)$ into Eq. (2), one obtains the delay correction $\tau_{\mathrm{ld}}(t)$ which has to be subtracted from the observed delay:

$$\tau_{\mathrm{ld}}(t) = \frac{1}{c} [\Delta\vec{\mathbf{r}}^1_{\mathrm{ld}}(t) - \Delta\vec{\mathbf{r}}^2_{\mathrm{ld}}(t)] \cdot \vec{\mathbf{k}}. \tag{4}$$

τ_{ld} depends on the difference of the two displacement vectors $\Delta\vec{\mathbf{r}}^i_{\mathrm{ld}}$ at time t and, therefore, on the length and the direction of the vectors $\Delta\vec{\mathbf{r}}^i_{\mathrm{ld}}$ (see Fig. 3). In addition, τ_{ld} is proportional to the cosine of angle θ between the difference vector and the direction of the source vector $\vec{\mathbf{k}}$. During an experiment the corrections τ_{ld} vary according to the variation of the displacement vectors $\Delta\vec{\mathbf{r}}^i_{\mathrm{ld}}$ with time as well as according to the specific direction of the observed radio source. Of course, τ_{ld} corresponds to the error contribution of the observed delays, if the atmospheric loading effect is disregarded.

Simulation of the effect of atmospheric loading on VLBI experiments

Air pressure changes by (anti-)cyclones

The effects of atmospheric loading on VLBI observations and on the parameters obtained in a baseline solution are investigated by studying the time dependence of station displacements for different models.

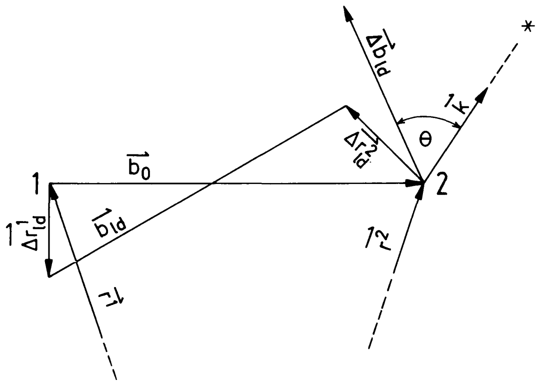

Fig. 3. Baseline-radiosource geometry of VLBI observations
$\vec{\mathbf{r}}^i$ - position vectors of VLBI stations $i=1,2$
$\vec{\mathbf{b}}_0$ - baseline vector under reference conditions
$\vec{\mathbf{b}}_{\mathrm{ld}}$ - baseline vector after consideration of the load-induced displacements $\Delta\vec{\mathbf{r}}^i_{\mathrm{ld}}$ of the VLBI stations $(i=1,2)$
$\Delta\vec{\mathbf{b}}_{\mathrm{ld}}$ - load-induced baseline difference $\vec{\mathbf{b}}_{\mathrm{ld}} - \vec{\mathbf{b}}_0$
$\vec{\mathbf{k}}$ - unit vector in source direction
θ - angle between $\Delta\vec{\mathbf{b}}_{\mathrm{ld}}$ and $\vec{\mathbf{k}}$

In order to use a realistic dataset for the simulations, real VLBI observations were taken from the MkIII experiment of 5/6 May 1983 of the transatlantic baseline between Effelsberg ($\varphi = 50°31'$, $\lambda = 6°53'$) and Haystack ($\varphi = 42°37'$, $\lambda = 288°30'$). The length of this baseline is approximately 6,000 km. A least-squares baseline solution of the 24-h dataset yields a delay rms σ_τ of 0.11 ns.

To separate the effect of the simulated air-pressure-induced displacements on the data analysis from other error sources, the original dataset has to be "optimized": the residuals of first analysis are added to the data in such a way that a repetition of the same process would yield error-free results. After this the air-pressure-induced delay corrections $\tau_{\mathrm{ld}}(t)$ are added and the "new" data set is analysed again to investigate the artificially introduced errors. Simulations of this kind have been carried out for the following types of station movements (see Fig. 4).

Model 1: linear change of vertical displacements $\Delta\mathbf{r}$ of both stations by 2 cm/24 h (acting in the same direction); no horizontal displacements (Fig. 4, top, left).

Model 2: linear change of vertical displacements $\Delta\mathbf{r}$ of station Effelsberg by +2 cm/24 h, of station Haystack by −2 cm/24 h; no horizontal displacements (Fig. 4, middle, left).

Model 3: sinusoidal change of vertical displacements of station Haystack with daily period and an amplitude of 1 cm; no displacement of Effelsberg; no horizontal displacements (Fig. 4, bottom, left).

Model 4: "mixed model"; non-linear changes of vertical and horizontal displacements of both stations (Fig. 4, right).

Extreme air pressure conditions will generate larger displacements than those supposed here. In this case the resulting delay corrections increase proportionally. In order to separate short periodic and seasonal air pressure effects, the vertical and horizontal displacements

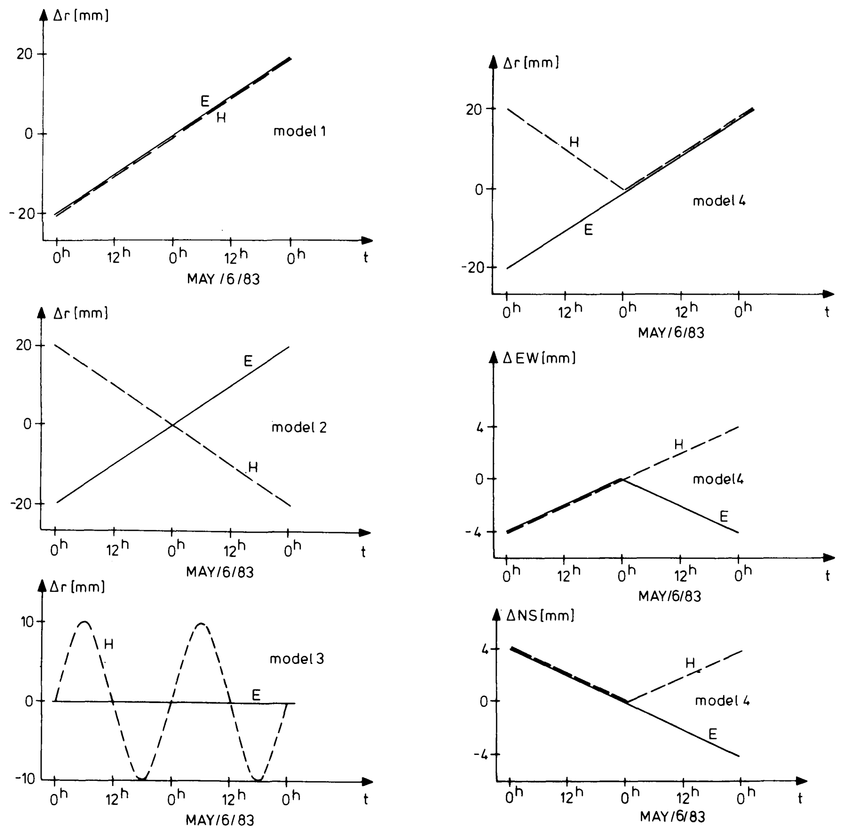

Fig. 4. Models of load-induced displacements used for simulations: E-Effelsberg, H-Haystack; Models 1–3, only vertical displacements; Model 4, vertical and horizontal displacements

are regarded as deviations from a mean station position due to a mean surface air pressure of 1,013 mbar.

For the simulations, the VLBI program package BVSS (Bonn VLBI Software System; Schuh, 1985) developed at the Geodetic Institute of the University of Bonn was used. In the standard solution of a single VLBI experiment the components of the baseline vector $\vec{b}$, the parameters of the clock model (i.e. the behaviour of the station clocks referred to a reference clock) and the parameters of a model of the tropospheric zenith delay ("atmospheric parameters") (Lundquist, 1984) are estimated. For the "optimal" dataset (see above), different combinations of the parameter groups of the VLBI model (baseline components, atmospheric parameters, clock parameters) were analysed. Thus, the influence of atmospheric loading on the various groups of unknowns can be separated. The influence on radio source positions and earth rotation parameters (pole coordinates and UT1 variations) was not examined. Whereas the positions of those radio sources which are normally observed in geodetic experiments are known with high precision and are usually fixed in single-experiment solutions, the earth rotation parameters in a single-baseline solution are directly connected with the baseline orientation and are therefore influenced equally.

The choice of the parameters to be solved was based on the following questions:

1. Does atmospheric loading decrease the precision of VLBI observations?

2. Are the baseline components, and above all the baseline length, affected?

3. Are the loading effects due to air pressure variations covered by those parameters of the VLBI model which are used for the description of tropospheric zenith delay?

4. Can the clock parameters of the VLBI model be used to remove air-pressure-induced errors? (With these parameters most of the systematic effects besides the clock behaviour can be removed.)

The results of the simulations are summarized in Table 1. As an example of the resulting delay corrections τ_{ld}, those of Model 2 are plotted in Fig. 5. It can clearly be seen that the opposite vertical displacements lead to a linear trend of the corrections, which can mainly be removed by a simple clock model with three parameters (reduction of the delay rms from 0.025 ns to 0.004 ns). The source specific differences mentioned previously, i.e. the dependence of the corrections on the direction of the source vector, can also be seen in Fig. 5.

Figure 6 shows the corrections which result from Model 4. Table 1 indicates that those more "accidental" contributions of atmospheric loading cannot be described completely: neither by the baseline components (decrease of σ_τ from 0.024 ns to 0.013 ns), nor by the clock parameters (decrease of σ_τ to 0.014 ns).

From the results in Table 1, further conclusions can be derived:

The effects of short-period atmospheric loads on VLBI stations can cause errors in the delay observations which, even in the worst cases, are below the actual VLBI precision of ± 3 cm ($=0.10$ ns). However,

Table 1. Delay rms σ_τ(ns) and change in baseline length Δb(mm) from simulations of the influence of different models of station displacements (Models 1–4) on the "error-free" dataset of the MkIII VLBI experiment from May 5–6, 1983, Effelsberg-Haystack baseline

Model	Error contribution from atmospheric loading (ns)	Delay rms σ_τ(ns) and change in baseline length Δb after solving for:			
		Only baseline components	Baseline components + atmospheric parameters	Only clock parameters (2nd order polynomial)	Baseline components + atmos. parameters + clock parameters
1	0.008	0.007 $\Delta b = -3$ mm	0.007 $\Delta b = -2$ mm	0.008	0.007 $\Delta b = -2$ mm
2	0.025 (Fig. 5)	0.024 $\Delta b = 1$ mm	0.024 $\Delta b = 7$ mm	0.004	0.004 $\Delta b = 0$ mm
3	0.017	0.016 $\Delta b = -2$ mm	0.016 $\Delta b = -5$ mm	0.009 with sine: 0.005	0.009 $\Delta b = -3$ mm 0.005 $\Delta b = -2$ mm
4	0.024 (Fig. 6)	0.013 $\Delta b = -6$ mm	0.013 $\Delta b = -8$ mm	0.014	0.008 $\Delta b = -6$ mm

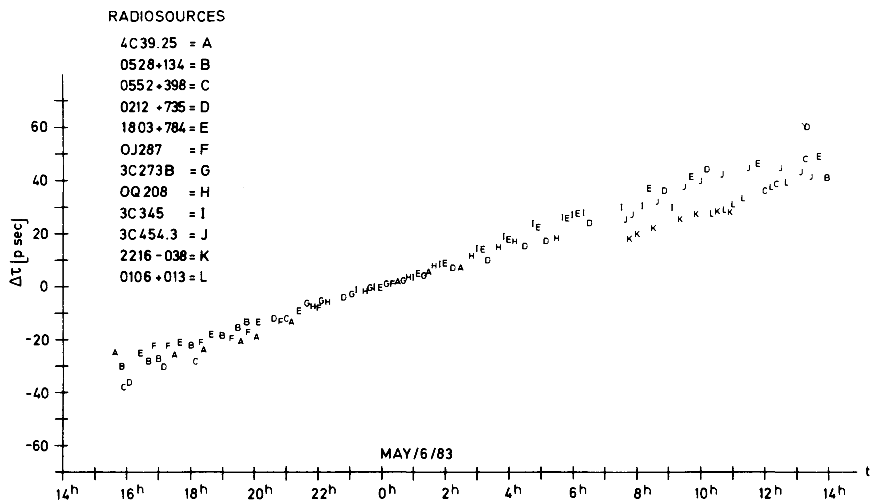

Fig. 5. Delay corrections τ_{ld} caused by the station displacements simulated in Model 2 (see Fig. 4, top, left)

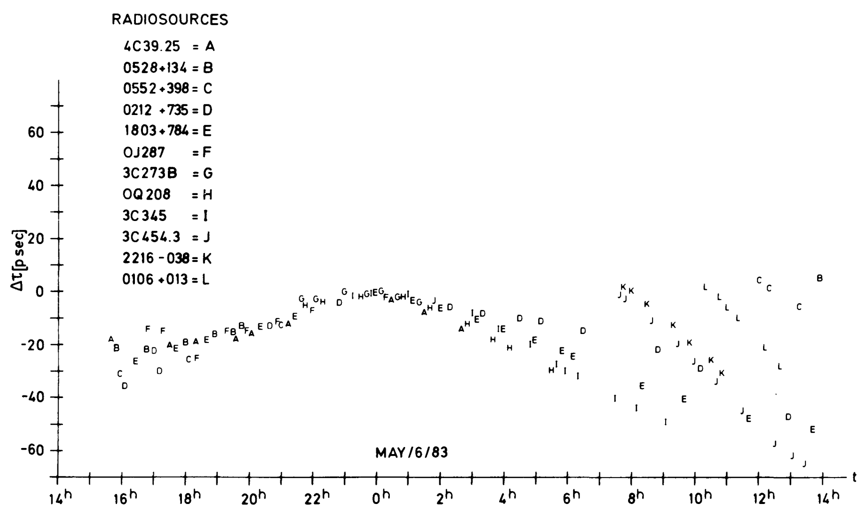

Fig. 6. Delay corrections τ_{ld} caused by the station displacements simulated in Model 4 (see Fig. 4, right)

to reach the general scope of the so-called "1-cm accuracy" they have to be considered.

The delay errors τ_{ld} can influence the baseline components derived in a geodetic solution, and, therefore, they can also falsify the baseline length. The change in the baseline length for the considered displacement models is within some millimetres. It will easily exceed 1 cm under more extreme conditions.

Except for special cases, the delay errors cannot be described by the general clock parameters of the VLBI

Table 2. Delay rms σ_τ(ns) and change in baseline length Δb(mm) from simulations of the influence of constant station displacements (Models 5 and 6) on the "error-free" dataset of the MkIII VLBI experiment from May 5–6, 1983, Effelsberg-Haystack baseline

Model	Error contribution from atmospheric loading (ns)	Delay rms σ_τ(ns) and change in baseline length Δb after solving for:			
		Only baseline components	Baseline components + atmospheric parameters	Only clock parameters (2nd order polynomial)	Baseline components + atmos. parameters + clock parameters
5	0.022	0.000 $\Delta b = -1$ mm	0.000 $\Delta b = 0$ mm	0.004	0.000 $\Delta b = 0$ mm
6	0.007	0.000 $\Delta b = -5$ mm	0.000 $\Delta b = -5$ mm	0.007	0.000 $\Delta b = -5$ mm

model (Models 2, 3). Anyway, a careful choice of the clock parameters is necessary: for example, in Model 2 using a polynomial the delay rms decreases only from 0.017 ns to 0.009 ns, whereas introducing a sine it is reduced to 0.005 ns.

Although the station displacements are caused by variations of surface air pressure, the resulting delay errors seem to be almost completely independent of the so-called atmospheric parameters. As can be seen from comparison of columns 3 and 4 of Table 1, the rms does not decrease when atmospheric parameters are included. Only the baseline lengths (as well as the baseline components) change. This can be traced back to the well-known high correlations between the station heights and the atmospheric parameters (Campbell et al., 1984).

Seasonal air pressure variations

The influence of global seasonal air pressure variations on VLBI observations has also been analysed using the test dataset. As can be seen from Eq. (4) and Fig. 3, constant station displacements do not lead to constant corrections τ_{1d}, because these depend on the specific radio source (by the angle θ).

In order to investigate the effect of long periodic changes on VLBI observables, the following constant vertical shifts of the stations were simulated:

Model 5: vertical displacement of Effelsberg +5 mm, of Haystack −5 mm

Model 6: vertical displacement of Effelsberg +5 mm, of Haystack +5 mm.

The corrections for Model 5 are shifted by a constant offset (+0.022 ns) and differ between 0.014 and 0.030 ns. The various solutions mentioned above were also computed for these models of constant displacements. The results are summarized in Table 2. Constant displacements, of course, are completely absorbed by the estimated baseline components. Depending on the configuration between baseline vector and station displacement vectors, not only the components but also the length of the baseline itself can change by several millimetres. Thus, for the 6,000-km Effelsberg-Haystack baseline a constant vertical displacement of +5 mm for both stations (Model 6) leads to a 5-mm change in the baseline length, as confirmed by the results of the least-squares solution ($\Delta b = 5$ mm in Table 2).

Conclusions

Concerning the interpretation of geodetic VLBI experiments, the following conclusions can be drawn:

1) Large-scale atmospheric loading causes errors in baseline length and station coordinates which are of the same order of magnitude as the VLBI precision. They are not corrected by today's standard VLBI data analysis methods (so-called clock- and atmosphere parameters). Therefore, magnitude and time-dependence of air-pressure-induced displacements should be evaluated by forward modelling.

2) Since the exact calculation of surface displacements by the method of Green's functions is rather laborious, it will not become a routine procedure for all world-wide VLBI experiments in the near future. On the other hand, the amplitudes of local and mean regional air pressure variations can easily be obtained from station logs and weather charts for the duration of the VLBI experiments. Equation (1) can then be used to calculate approximate correction values for the vertical displacements. If higher accuracy is required, the method of Green's functions has to be applied. For the present, however, this will be necessary only for a few VLBI experiments.

3) At the moment, all radiotelescopes used for geodetic experiments are situated in areas with less than ±2 mm seasonal variation in the vertical displacement. Increasing VLBI accuracy and an expanding VLBI network will also require the consideration of seasonal displacements which can exceed the 1-cm limit. Seasonal variations of station position can easily be included in every VLBI data analysis program.

This paper has only treated the atmospheric loading effect on VLBI stations. The procedure that has been applied can be used to treat all deformation effects of similar character. The envisaged 1-cm accuracy for geodynamic investigations (e.g. NASA's Crustal Dynamics Project, see NASA, 1984) requires, in addition, the consideration or investigation of other exogenic surface deformations as caused by body tides, ocean loading tides, long-term variations of the sea level, local groundwater level or snow loading (e.g. see Varga, 1981; Scherneck, 1983).

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