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WAYS TO IMPROVE MEASUREMENT ACCURACY OF ATMOSPHERIC TRACE GAS PARAMETERS: HARDWARE AND DATA PROCESSING

Subject and Purpose. *Analysis of ways to increase the accuracy of determining the parameters of the Earth's atmosphere through the improvement of the ground-based spectral radiometric complex designed for monitoring carbon monoxide (CO) by millimeter radio wave radiation control, which was developed at the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine The purpose is achieved by reducing the measurement errors of the emission amplitude of the observed tracer gas through the operational determination of the absorption of radio waves in the troposphere. By performing a rapid calibration of the troposphere opacity and promptly accounting for changes in radio signal absorption, we increase the accuracy and reliability of measurements of atmospheric CO radio emission intensity. This method is suitable for any systems of this type. By studying the frequency stability of local oscillators of all stages of frequency conversion in the receiving system, the maximum error in measuring stratospheric wind speeds at altitudes from 20 to 80 kilometers was determined.*

Methods and Methodology. *The improved CO-monitoring setup measures radiometric atmospheric profiles, from which a new data processing method introduced in the paper quickly derives the antenna scattering coefficient. Then, the tropospheric absorption of the radio signal is evaluated immediately during monitoring in near-real time.*

Results. *The CO-monitoring spectroradiometric complex has been upgraded and improved, enabling the measurement of radiometric atmospheric profiles and providing a prompt, near-real-time determination of the antenna scattering coefficient (previously unavailable). It has been demonstrated that monitoring the antenna scattering coefficient enhances the determination accuracy of the CO emission line amplitude, thereby increasing the reliability and validity of the obtained results. The studies related to the modernization of the monitoring instrument helped us evaluate the accuracy of measuring stratospheric wind speeds.*

Conclusion. *Practical work and evaluations have proved that measuring tropospheric opacity directly during observations is feasible and significantly increases the accuracy and reliability of the results.*

Keywords: *millimeter waves, aeronomy, measurement accuracy.*

Introduction

In the present state of the art, research into the physical characteristics of the Earth's atmosphere increasingly employs ground-based facilities. Compared to methods utilizing airborne and spaceborne equipment, the surface-based counterparts provide valuable physical information at relatively low costs. The most widely used ground-based instruments are microwave spectrometers intended to monitor the so-called trace (indicator) gases, including ozone (O_3), carbon monoxide (CO), and nitrous

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oxide (N_2O) [1—5], which are present in infinitesimal amounts in the atmosphere, their partial shares not exceeding 0.1%. The shape analysis of the emission lines provides insights into the environments of O_3, CO, and N_2O molecules, offering the pressure, temperature, and the speed and direction of molecular motion. The measurements are not taken point by point but produce vertical cross-mesospheric profiles that sometimes extend into the troposphere. The millimeter-wave observations, compared to shorter wavelengths, have the advantage of continuously measuring the region both day and night and even during cloudy conditions. We understandably mean the upper millimeter waves, above 100 GHz, as emission lines at lower frequencies are physically absent.

The above-mentioned cross-mesospheric profile is used to track atmospheric states at various altitudes, occupying a happy position when more than one trace gas is simultaneously monitored. Thus, the ozone O_3 molecular emission provides insights into atmospheric states within the 10 to 60 km altitude range [6—10]. From about 60 to 85 km above the Earth, carbon monoxide CO alone can track atmospheric dynamics there. In the Earth's mesosphere, CO is only produced through the photodissociation of carbon dioxide molecules. While CO_2 emission in the microwave region is unobservable, CO emission is detected at 115.27 GHz to provide valuable information about, e.g., global warming due to elevated CO_2 amounts in the atmosphere. Another point in favor of carbon monoxide is that a lifespan of CO molecules in the upper atmospheric layers exceeds a month, which offers a unique opportunity to study such dynamic processes as mesospheric winds [11, 12].

The emission line is characterized by 1) emission line center frequency, 2) line amplitude with due regard for tropospheric opacity, which is in itself a valuable asset, and 3) line shape. These characteristics are like fingerprints reflecting the traits of CO molecule environments at different altitudes. Furthermore, their measurements with ground-based spectroradiometers are robust and can be made 24/7 throughout the year, regardless of weather conditions. The ultimate aim of the measurements is to continuously monitor atmospheric physical parameters (pressure and temperature) at stratospheric altitudes by measuring the amplitude and shape of the CO emission line above a specific geolocation site.

Another type of problem is the dynamics of stratospheric air masses. Its solution lies in studying the frequency shifts of the CO emission line. A remarkable atmospheric effect, where microwave spectroradiometers are used to advantage, is the sudden stratospheric warming (SSW) marked by abrupt reversals of stratospheric winds over short periods [13, 14]. Produced by horizontal redistribution of air masses due to strong planetary wave activity [14—16], the SSW events occur roughly every few years in the polar and circumpolar regions, regarded as the "weather factory", and make the stratospheric temperatures suddenly rise by more than ten degrees. These aeronomic effects are usually studied via CO and O_3 monitoring from ground-based measurement stations [17—19]. Long-term wind parameters at various altitudes are retrieved without resort to spaceborne instruments, whose acquisitions, however, are often used for comparison. Thus, for example, in the analysis of SSW processes in 2018—2019 [20], the observation data from a measuring campaign using a microwave spectroradiometer located at 50.0° N, 36.30° E, the RI NASU, Kharkiv, Ukraine [21] were treated in tandem with acquisitions of the microwave limb sounder (MLS) on the Aura satellite [22, 23]. Because of the satellite motion, MLS stratospheric-state data sets above geolocation sites appear smeared. A ground-based microwave spectroradiometer conducts continuous observations but is limited to a specific location. Spaceborne radiometry and ground-based measurements complement each other effectively. But in joint processing of data from various sources, one must always check whether the accuracies of the initial measurements by the two methods are compatible and should methodologically (mathematically) minimize systematic unavoidable errors lest the accuracy be lost.

Earlier, when the measurement errors from the CO-measuring aeronomic system created at the RI NASU were discussed in [24], no studies other than statistical data analysis were available. After completing some upgrades, we can retrieve vertical atmospheric profiles, from which additional setup parameters (such as the antenna scattering coefficient) are extracted, with the tropospheric opacity constant known in near-real time. The outcomes and methods discussed in the article are relevant to any trace-gas monitoring, including ozone. Being aware of them is strongly recommended when operating a hetero-

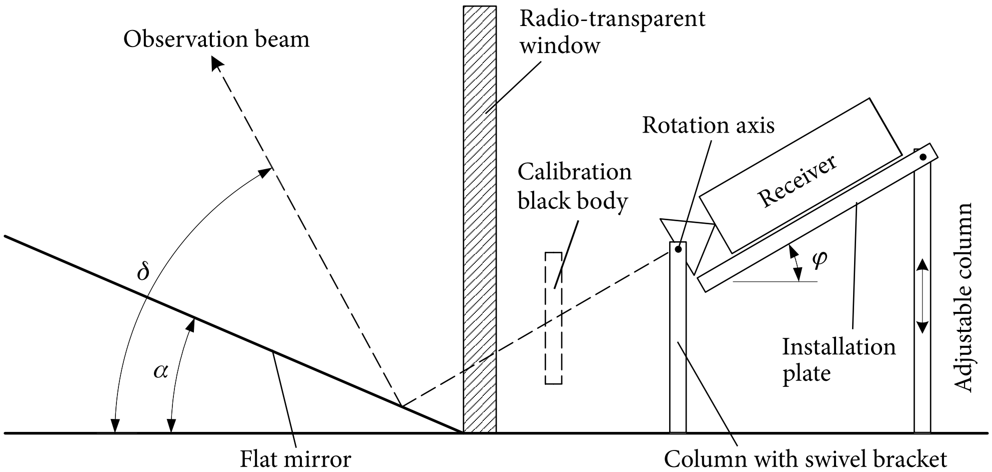

Fig. 1. Schematic of the atmospheric profile retrieval

dyne receiver in double-sideband mode and during changing cloud conditions. Understandably, prompt adjustments to the current atmospheric opacity is necessary, or data scatter is inevitable.The main errors in CO spectrum observations are scrutinized. They relate to the estimation accuracy of the emission line amplitude recalculated for the troposphere and the measurement accuracy of the CO emission line central frequency.

1. Tropospheric opacity monitoring

At the Institute of Radio Astronomy of the NASU in Kharkiv, a stratospheric CO-monitoring complex was established for, among other things, detecting, tracking, and studying stratospheric winds effectively identified through CO emission monitoring in the atmosphere [10, 12]. The radio-transparent window of the setup faces east and offers 45° elevation angle observations.

The modernization of the current CO-monitoring setup aims to enable prompt retrievals of atmospheric profiles and obtain atmospheric opacity data with no delay. In doing so, the existing setup geometry is kept undisturbed. The receiver involved in the CO monitoring scheme consists of two units, a receiver itself and a local oscillator block, both mounted on a common installation plate (Fig. 1). In our case, the most practical instrument solution for atmospheric profile retrieval is tilting the installation plate by an angle φ within 0 to 25 degrees. The best option is revolving the receiver around the rotation axis (Fig. 1), which passes through the center of the receiving horn aperture.

According to the schematic in Fig. 1, the elevation angle, δ, at which the observation holds, changes as the installation plate carrying the receiver is tilted by a φ angle, causing the installation plate corner to rise. The elevation angle is derived as

$$\delta = 2\alpha + \varphi, \qquad (1)$$

where α is the tilt angle of the flat mirror.

In the existing setup geometry, the receiver system is tiltable by up to $\varphi \approx 25°$, while the observation beam angle δ (1) can vary within 45 to 70°. For atmospheric profiles, this range of angles is the most informative [25, 26]: at larger angles, the sky temperature changes very little, while at smaller angles, the environment can interfere with the data.

The elevation angle of the monitoring is 45°. The receiver-carrying installation plate (Fig. 1) is positioned horizontally ($\varphi = 0$). The heated flat mirror behind the window is tilted to the horizon at $\alpha = 22.5°$.

During stratospheric CO measurements, the receiver system is calibrated every thirty minutes by putting the calibration black body in front of the horn (see Fig. 1) for one minute. The calibration black body, an absorber with its temperature known, is mounted on a movable carrier. Another calibrator with a known temperature is the intrinsic noise temperature of the receiver system. The output voltage of the receiver system in this calibration procedure can be written as

$$U_{cal} = ck_b \Delta f (T_{rec} + T_l), \qquad (2)$$

where c is the transmission coefficient of the receiver-amplifier path including a square-law video detector, k_b is the Boltzmann constant, Δf is the instantaneous bandwidth of the receiver working frequencies, T_{rec} is the receiver noise temperature, and T_l is the calibration black body temperature equal to the room temperature.

The authors' scientific experience and the evaluation of other receiver systems [17] ensure that the intrinsic noise temperature of the receiver is quite a stable value. The control measurements that we took every six months for four years confirmed that the noise temperature of the double-sideband receiver system we used was 300 K and was faithfully reproduced within the measurement error in all control measurements.

In the used scheme of calibration, the CO emission intensity is readily obtained in Kelvins. Yet, the CO emission is observed across the troposphere, whose opacity is very much determined by the weather. Therefore, to evaluate the CO radiation intensity beyond the troposphere, the tropospheric opacity, τ, must be taken into account.

Previously, we struggled to determine the tropospheric opacity quickly and accurately, but relative errors in emission intensity exceeded 10%, especially during adverse weather conditions. Now, after the CO-monitoring setup improvement and with our new method of atmospheric profile processing, we have more resources. The output voltage, U_s, across a wide-band receiving channel, such that the receiving frequency bandwidth exceeds the bandwidth of the emission line, is derived as

$$U_s = ck_b\Delta f\left[T_{rec} + \beta T_l + (1-\beta)T_{ant}(\Theta)\right], \qquad (3)$$

where β is the scattering coefficient of the antenna system and Θ is the elevation angle at which the sky emission is received. Ibidem,

$$T_{ant}(\Theta) = T_{eff}\left(1 - e^{-\frac{\tau}{\sin\Theta}}\right), \qquad (4)$$

where T_{eff} is the effective tropospheric temperature. Traditionally, $T_{eff} = 0.95T_{amb}$, with T_{amb} being the ambient temperature.

Expressions (2)—(4) determine the CO emission intensity highly reliably outside the troposphere. Calibration formula (2) yields the output voltage U_s in Kelvins. From (4), one readily finds the tropospheric opacity constant τ, given $T_{ant}(\Theta)$ in expression (3) is known. The problem is that expression (3) involves the antenna scattering coefficient β, which makes troubles. No matter that the antenna scattering coefficient is a value of great utility, it is not readily available. Its evaluation requires having an anechoic chamber and complex measuring equipment. Moreover, the test-bench results can vary considerably from the actual values due to the influence of the real antenna environment.

The method we proposed in [27] determines the antenna scattering coefficient via a new technique for atmospheric profile processing. With the known scattering coefficient β of the antenna system, one can quickly derive the tropospheric opacity τ from expressions (3) and (4). This opacity is then utilized during CO emission monitoring to refine the measurement results of emission intensity. The accuracy of opacity τ determination depends on the total emission which is registered across the whole monitoring band. As monitoring time intervals are on the order of hours and receiver sensitivity is as high as T_{rec} = 300 K, the fluctuation sensitivity of the spectral analyzer with an 8 MHz bandwidth will be better than 1 K, which is more than adequate for determining τ. Therefore, we limit ourselves to upgrading the program for monitoring data processing without wide-band channel data, which would have complicated the hardware of the CO-monitoring system.

The data processing program contains one more innovation. The double-sideband receiver is used in a frequency band where the sky temperatures in the upper and lower sidebands are quite different, hence different amounts of tropospheric opacity τ. For how to derive tropospheric opacity τ from the double-sideband receiver monitoring outputs, see [30]. This extension to the data processing program essentially refines the determination of CO emission intensity.

2. Stratospheric wind determination accuracy

Studying stratospheric winds is one of the main reasons justifying our setup for atmospheric monitoring by CO microwave emission. Stratospheric winds are seasonal events. They have been intensively studied in recent years [11, 12, 28]. At altitudes between 70 and 90 kilometers, the wind speed in the stratosphere

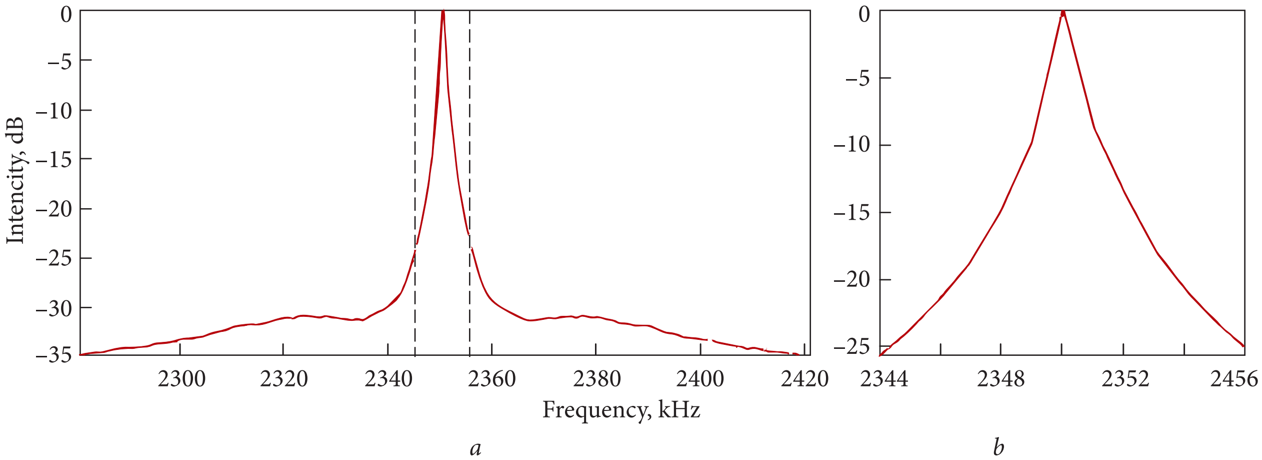

Fig. 2. The total spectral characteristic of the local oscillators of the receiver system

is measured through the Doppler shift acquired by the emission frequency as the source moves toward the observer. By this effect, the radial velocity of CO molecules is defined as

$$V = c\delta f / f, \quad (5)$$

where δf is the shift of the emission line center and f is the frequency of the emission line center of an immobile CO molecule.

Formula (5) indicates that the total spectrum width of all the local oscillators that translate the considered emission frequency to the operating band of the existing spectrum analyzer establishes an area of uncertainty in the wind speed determination. The frequency instability of the local oscillators causes measurement errors, affecting the accuracy of wind speed determination and its lowest registerable value. At survey frequencies around 100 GHz, a 10 kHz frequency shift occurs at a wind speed of 30 m/s. To catch and track stratospheric winds, the CO emission line is particularly suitable due to its narrow (270 kHz) intrinsic spectral linewidth (without external factors of broadening) in the free state. At the same time, the measurements of the kind are demanding on the frequency stability of all the oscillators incorporated into the spectroradiometer.

For our CO-monitoring receiver, highly stable solid-state phase-locked loop (PLL) oscillators were developed as local oscillators in all mixing stages. These PLL oscillators can work continuously for long periods, which is crucial for effective monitoring. Sadly, the entire receiver is quite a complex system. It needs calibration procedures and frequency stability control. We use an integrated method that simultaneously checks the frequency stability of all the oscillators. In this method, the receiver input is fed with a signal from a high-quality oscillator at the CO line frequency, which is the local oscillator of the spectral radio astronomical receiver system. This oscillator is far away (50 meters) from the CO-monitoring setup, in a separate, air-conditioned room. By this reason, each oscillator is equipped with a 5-MHz Oven-Controlled Crystal Oscillator with a relative instability of ±50 ppb per month.

The estimated value of the signal bandwidth broadening observed on the spectrum analyzer in CO monitoring is governed by the relative instability of the local oscillator frequency. At around 100 GHz, the broadening will not exceed 1 kHz. The test signal path leading to the receiver input was not particularly designed. Instead, a mirror is installed in front of the horn to boost the signal level on the high-sensitivity spectrum analyzer until nonlinear transformations emerge, while ensuring that the output signal dynamic range is at its maximum. This signal is certainly a frequency convolution of signals from the external oscillator and the receiving system oscillators used for the frequency transformation. Naturally, the higher the external oscillator signal quality, the closer the observation is to the real-world performance of the frequency transformation system. In this case, the so identified characteristics should be thought of as an estimate "from above".

A typical signal observation during this testing is illustrated in Fig. 2. The left panel shows that the total spectrum width of the employed solid-state PLL local oscillator is not over 20 kHz at the –30 dB level. The right panel enlarges the spectrum fragment given on the left and enclosed between the dotted straight lines. The spectrum width at the –20 dB level is not over 7 kHz. The actual width is narrower because the mutual detuning of the reference frequency sources takes more effect in this part of the spectrum. It is the local oscillator spectrum width that primarily affects stratospheric wind speed measurement results. The absolute error from our spectroradiometer does not exceed 10 m/s, and the relative error is about 10%.

Hence, the testing of the frequency stability of the characteristics of the CO-monitoring receiver system has confirmed that accurate recordings of stratospheric winds are feasible indeed. The stratospheric winds are seasonal events. However, they can display intriguing physical phenomena, such as sudden stratospheric warmings [29].

Conclusions

The upgrades we have made to our atmospheric CO-monitoring setup and the precise measurements of its characteristics have continued the work on improving and validating the aeronomic complex started at the Institute of Radio Astronomy of the NASU with the development of the ozone monitoring complex [27, 30]. The new method for studying electromagnetic wave absorption in the troposphere (tropospheric opacity) enhances the accuracy of measuring the CO molecular emission intensity by promptly determining atmospheric opacity. By assessing the spectral purity of the used local oscillators, we have identified errors in the mesospheric wind speed measurements. The authors believe that the suggested approach will be helpful for both developers of new ground-based aeronomic systems and specialists seeking to enhance existing equipment.

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СПОСОБИ УДОСКОНАЛЕННЯ ТОЧНОСТІ ВИМІРЮВАННЯ ПАРАМЕТРІВ АТМОСФЕРНИХ ТРАСЕРНИХ ГАЗІВ: АПАРАТНЕ ЗАБЕЗПЕЧЕННЯ ТА ОБРОБКА ДАНИХ

Предмет і мета роботи. Аналіз шляхів підвищення точності визначення параметрів земної атмосфери через вдосконалення розробленого в Радіоастрономічному інституті НАН України спектрального радіометричного комплексу наземного базування, призначеного для моніторингу монооксиду вуглецю (СО) по випромінюванню міліметрових радіохвиль. Мета досягається шляхом зменшення похибок вимірювання амплітуди випромінювання спостережуваного трасерного газу через оперативне визначення поглинання радіохвиль у тропосфері. Здійснюючи швидке калібрування непрозорості тропосфери та оперативно враховуючи зміни, що відбуваються в поглинанні радіосигналу, ми підвищуємо точність і достовірність вимірювань інтенсивності радіовипромінювання атмосферного СО. Цей метод придатний для будь-яких систем подібного типу. Через дослідження стабільності частоти гетеродинів усіх ступенів перетворення частоти в приймальній системі визначено величину максимальної похибки при вимірюванні швидкостей стратосферних вітрів на висотах від 20 до 80 кілометрів.

Методи та методологія. У статті показано шляхи удосконалення системи моніторингу трасерного СО, за допомогою якого вимірюються радіометричні профілі атмосфери. Запропоновано новий метод обробки даних, що дозволяє швидко визначати коефіцієнт розсіювання антени. Надалі тропосферне поглинання радіосигналу оцінюється безпосередньо під час моніторингу в режимі, близькому до реального часу.

Результати. Спектрорадіометричний комплекс для моніторингу трасерного СО було модернізовано та удосконалено, що дозволило вимірювати радіометричні профілі атмосфери й забезпечувати оперативне визначення коефіцієнта розсіювання антени (що раніше було неможливо) майже в режимі реального часу. Продемонстровано, що моніторинг коефіцієнта розсіювання антени підвищує точність визначення амплітуди лінії випромінювання СО, тим самим збільшуючи надійність і валідність отриманих результатів. Дослідження, пов'язані з модернізацією приладу моніторингу, допомогли нам оцінити точність вимірювання швидкості вітру в стратосфері.

Висновки. Аналітично та на практиці доведено, що вимірювання непрозорості тропосфери безпосередньо під час спостережень є можливим і значно підвищує точність і надійність результатів.

Ключові слова: *міліметрові хвилі, аерономія, точність вимірювання.*