ALMA Memo 384
Atmospheric Transparency at Chajnantor and Pampa la Bola

Simon J. E. Radford and Bryan J. Butler
National Radio Astronomy Observatory

Seiichi Sakamoto
National Astronomical Observatory of Japan

Kotaro Kohno
Nobeyama Radio Observatory

2001 August 2

Abstract

Measurements with 220 and 225 GHz tipping radiometers demonstrate the atmosphere over both Chajnantor and Pampa la Bola has exceptional transparency, better than observed over Mauna Kea. These measurements indicate, however, the atmosphere is more transparent at Chajnantor than at Pampa la Bola. For hourly median optical depths from 1999 June through 2000 December, the median at Pampa la Bola is 0.011 larger than at Chajnator and the median normalized difference is $[\tau_{220}(\mathrm{Bola}) - \tau_{225}(\mathrm{Chaj.})]/\tau_{225} = +0.23$. Side-by-side measurements at Chajnantor in 2001 April–May confirm the data from the two instruments can be directly compared. The measured transparency differences imply Chajnantor enjoys a significant advantage in observing time or sensitivity, especially for observations at submillimeter wavelengths.

Introduction

Atmospheric transparency presents a fundamental limitation to the speed and sensitivity of observations at millimeter and submillimeter wavelengths. In planning the ALMA project, therefore, the partner institutions have expended considerable effort to assess and select an outstanding site in the high Andes of northern Chile. This area, around Cerros Chajnantor and Chascón, has been designated a science preserve by the Chilean goverment. It has exceptional atmospheric transparency, ranking among the premier sites for millimeter and submillimeter wavelength astronomy. In particular, the area enjoys better conditions than Mauna Kea (Figure 1; Radford & Chamberlin 2000).

Within the science preserve, measurements of atmospheric transparency have been carried out at two particular locations. Since 1995 April, the NRAO has operated a 225 GHz tipping radiometer on the Llano de Chajnantor (5050 m) about 4.3 km south-southwest of Cerro Chajnantor (Radford & Holdaway 1998). In 1996 July, the NRO installed a similar 220 GHz tipping radiometer at Pampa la Bola, about 250 m lower than and 8 km NE of the NRAO instrument (Ishiguro et al. 1998). Data from these instruments confirm both sites are excellent but suggest the transparency at Chajnantor is significantly better than at Pampa la Bola.

Instruments

The NRAO tipping radiometer (Liu 1987; McKinnon 1987) is a DSB heterodyne receiver operating at 225 GHz with a 1.0–1.5 GHz IF bandpass. (Because the earlier memos give inconsistent descriptions of the passband, we have reconfirmed the actual band width.) An internal chopper continuously switches the receiver input between two calibration loads (45°C and 65°C) and an offset parabolic mirror that scans the sky. The radiometer measures the atmospheric transparency every 10 min except for one hour every 4.5 h, when the transparency measurements are suspended while the receiver measures fluctuations in the sky brightness. Since 1998 June, the instrument clock has been synchronized to within one second of UTC by a GPS receiver. Before that, the clock was kept within a few minutes of UTC by monthly telephone calls to the NIST time service. Through 2001 July, the instrument has operated 84% of the time. Because of various instrument failures, however, data are sparser in early 2000 than in other years.

The NRO tipping radiometer is also a DSB heterodyne receiver (Kohno et al. 1995). Although known as the 220 GHz radiometer, it actually operates at 218.5 GHz with a 1.0–1.4 GHz IF bandpass. It determines the transparency about once per minute. The system clock is set during periodic maintenance visits.

Both instruments measure the sky brightness at several zenith angles to determine the atmospheric transparency. For a conventional simple atmospheric model of a plane parallel isothermal slab, the (monochromatic) sky brightness temperature,

$$T_{\rm sky}(z) = T_{\rm atm}(1 - e^{-\tau A}), \tag{1}$$

where τ is the atmospheric optical depth at the zenith, $T_{\rm atm}$ is the effective atmospheric radiation temperature, and $A = \sec(z)$ is the airmass at zenith angle z. Both radiometers make single sided tips from the zenith down towards the horizon. As a result, they might measure systematically higher or lower optical depths if they were not precisely level. At Chajnantor, the NRAO tipper scans toward the eastern horizon. At Pampa la Bola, the NRO instrument scans toward the western horizon.

Data

Simultaneous data from both instruments exist for most of the time since 1999 June and sporadic data exist for 1996 and 1997 (Table 1). All months of the year are represented except January and February, which are absent because of complementary instrument failures in 2000 and 2001. During 2001 March–May, the NRAO radiometer suffered a partial software malfunction. Those data have been edited accordingly, but remain lower quality than for other periods.

For detailed comparison, the data were paired by selecting the first Pampa la Bola measurement within 1 min of each Chajnantor measurement. This synchronization is perhaps overly strict. The sites are 8 km apart, which corresponds to a 20 min delay at the median surface wind speed, $6.5\,{\rm m\,s^{-1}}$ (Radford & Holdaway 1998), and winds aloft tend to be faster than surface winds. Furthermore, although the relative synchronization of the instrument clocks appears adequate, the actual synchronization precision is unknown.

Because substantial changes in transparency do not occur quickly, exact data synchronization is not essential for meaningful site comparison and sampling the same diurnal, seasonal, and weather cycles is sufficient. For an overall view, therefore, the median optical depths were determined for each hour from 1999 June through 2001 December when data were available for both sites.

Both instruments see similar overall weather patterns (examples in Figures 2, 4, & 6). Substantial changes in transparency do not happen quickly, but occur over periods of hours or longer.

For 1999 June and subsequent months, the paired data are generally well correlated, with linear correlation coefficients $r \geq 85\%$ (examples in Figures 3, 5, & 7). As a rule, however, the measured transparency is better at Chajnantor than at Pampa la Bola. The monthly median optical depths at Pampa la Bola are typically between 0.01 and 0.02 larger than at Chajnantor (Table 1). In relative terms, the monthly median normalized differences, $[\tau_{220}(\mathrm{Bola}) - \tau_{225}(\mathrm{Chaj.})]/\tau_{225}$ are typically +0.1 to +0.4.

A similar difference between the sites is evident from comparison of the hourly median optical depths (Figure 8). In these data, the median at Pampa la Bola, $\tau_{220}(\mathrm{Bola}) = 0.054$, is 0.011 larger than the median at Chajnantor, $\tau_{225}(\mathrm{Chaj.}) = +0.043$ (Table 1). The median normalized difference is $[\tau_{220}(\mathrm{Bola}) - \tau_{225}(\mathrm{Chaj.})]/\tau_{225} = +0.23$.

The paired data from 1996 and 1997, on the other hand, are often poorly correlated, suggesting an instrument problem such as a clock offset. Although these data also indicate better conditions at Chajnantor, they are not a reliable basis for comparison and are excluded from the overall statistics.

Instrument Comparison

The two instruments operate with different frequencies (218.5 and 225 GHz) and bandwidths (1.0–1.4 and 1.0–1.5 GHz). Might these differences explain the observed results?

For these radiometer parameters and 1 mm of water vapor over a 5000 m high site, the ATM atmospheric model (Pardo et al. 2001) predicts $\tau_{220} = 0.047$ and $\tau_{225} = 0.053$, or $(\tau_{220} - \tau_{225})/\tau_{225} = -0.11$. The difference is largely caused by an O_3 line in the upper side band of the 225 GHz radiometer. This prediction of *larger* optical depths at 225 GHz with the NRAO radiometer cannot explain, however, the observations of larger optical depths at 220 GHz with the NRO radiometer on Pampa la Bola.

Intercomparison observations have been made on two occasions. On 1994 November 5–6, the two radiometers were run side by side at the Paranal base camp ($\approx$ 2000 m) for somewhat more than 24 h. This test indicated good agreement, $|\tau_{220} - \tau_{225}| < 0.01$ (Holdaway et al. 1996) when the median τ_{220} was 0.13. Conditions at both Chajnantor and Pampa la Bola are considerably better than at the Paranal base camp, however, and the observed differences between the high sites are about the same magnitude as the precision of the agreement in the Paranal comparison.

From 2001 April 24 to May 2, therefore, the two instruments were operated side-by-side at Chajnantor, scanning parallel to each other. The weather was variable, including very good ($\tau_{225} < 0.03$) and mediocre ($\tau_{225} \approx 0.3$) conditions (Figure 9). Over this range, the measured optical depths agree very well (Figure 10). The median normalized difference, $(\tau_{220} - \tau_{225})/\tau_{225} = -0.03$, has the same sense as the model prediction, albeit with a smaller magnitude. During this comparison, the NRAO radiometer measured slightly larger optical depths than the NRO instrument.

The agreement between the instruments during these intercomparisons was very good, much better than the typical observed difference between the sites. Hence the data for Pampa la Bola and Chajnantor can be directly compared.

Implications

At 220/225 GHz, the absolute value of the measured difference in atmospheric transparency between Chajnantor and Pampa la Bola is small. The differences in the monthly median optical depths $\tau_{220}(\text{Bola}) - \tau_{225}(\text{Chaj.})$ generally lie between +0.01 and +0.02 (Table 1). This small transparency difference implies, however, a substantial difference in observing time, especially at submillimeter wavelengths.

The integration time, t, required to acheive a certain sensitivity depends on the square of the system noise, T_{sys},

$$t \propto T_{\text{sys}}^2 = e^{2\tau A} \left[T_{\text{rec}} + T_{\text{atm}} \left(1 - e^{-\tau A} \right) \right]^2 , \tag{2}$$

where T_{rec} is the receiver temperature.(Secondary effects, including ground spillover and the cosmic background radiation, have been neglected.) Then to reach the same sensitivity in observations under two conditions, τ_1 and τ_2, the ratio of the required integration times

$$t_1/t_2 = (T_{\mathrm{sys},1}/T_{\mathrm{sys},2})^2 \tag{3}$$

$$= e^{2(\tau_1-\tau_2)A}\left[\frac{T_{\mathrm{rec}}+T_{\mathrm{atm}}\left(1-e^{-\tau_1 A}\right)}{T_{\mathrm{rec}}+T_{\mathrm{atm}}\left(1-e^{-\tau_2 A}\right)}\right]^2. \tag{4}$$

Based on observations at Pampa la Bola (and Chajnantor) with a Fourier transform spectrometer, Matsushita et al. (1999, 2000) derive linear regressions between the optical depths at different frequencies, $\tau(\nu) = a(\nu)\,\tau_{220} + b(\nu)$ (Table 2). These measured regressions allow an extrapolation to higher frequencies of the measured difference between the transparency at Pampa la Bola and Chajnantor. (This extrapolation may not be valid for other sites.) The ALMA project goals are receivers with noise temperatures limited to a few times the quantum limit, for example $T_{\mathrm{rec}} \leq 5h\nu/k$ (Wild & Payne 2001). At tropical latitudes, the median airmass for transit observations of uniformly distributed sources at $z < 60°$ is $A = 1.1$. Take, as an illustration, these factors together with $\tau_2 = 0.04$, which is the first quartile of the long term distribution at Chajnantor (Figure 1), and $(\tau_1 - \tau_2)/\tau_2 = +0.25$, which is typical for the measured difference between Pampa la Bola and Chajnantor. Then the observing time (or sensitivity) advantage enjoyed by Chajnantor, which is modest, but significant, at millimeter wavelengths, becomes dramatic for submillimeter observations (Table 2). Considering median conditions or observations at a larger airmass would further enhance the contrast between the sites.

Conclusions

At 220/225 GHz, both Chajnantor and Pampa la Bola have better atmospheric transparency than found at Mauna Kea. The measured transparency is, however, better at Chajnantor than at Pampa la Bola. For hourly median optical depths from 1999 June through 2000 December, the median at Pampa la Bola is 0.011 larger than at Chajnator and the median normalized difference is $[\tau_{220}(\mathrm{Bola}) - \tau_{225}(\mathrm{Chaj.})]/\tau_{225} = +0.23$. Side-by-side measurements with both instruments at Chajnantor in 2001 April–May confirm the data from the two instruments can be directly compared. The measured transparency difference implies Chajnantor enjoys a significant advantage in observing time or sensitivity, especially for observations at submillimeter wavelengths.

Acknowledgements

We thank Angel Otárola for keeping the instruments functioning and Mark Holdaway, Frazer Owen, and Bob Brown for helpful comments and suggestions.

References

Holdaway, M. A., Ishiguro, M., Foster, S. M., Kawabe, R., Kohno, K., Owen, F. N., Radford, S. J. E., & Saito, M., 1996, MMA Memo 152

Ishiguro, M., et al., 1998, Proc. SPIE 3357, 244

Kohno, K., Kawabe, R., Ishiguro, M., Kato, T., Otárola, A., Booth, R., & Bronfman, L. 1994, NRO Tech. Rept. 42

Liu, Z.-Y., 1987, MMA Memo 41

Matsushita, S., Matsuo, H., Pardo, J. R., & Radford, S. J. E., 1999, PASJ 51, 603

Matsushita, S., Matsuo, H., Sakamoto, A., & Pardo, J. R., 2000 Proc. SPIE 4015, 378

McKinnon, M., 1987, MMA Memo 40

Pardo, J. R., Cernicharo, J., & Serabyn, E., 2001, IEEE Trans. Ant. Prop. in press

Radford, S. J. E., & Holdaway, M. A., 1998, Proc. SPIE 3357, 486

Radford, S. J. E., & Chamberlin, R. A., 2000, ALMA Memo 334

Wild, W., & Payne, J., 2001, ALMA Project Book Chapter 5

Table 1: Simultaneous (Paired) Data

month	r	median τ_{225} Chaj.	median τ_{220} Bola	median $\frac{\tau_{220}-\tau_{225}}{\tau_{225}}$	remarks
1996 July	0.77	0.069	0.109	+0.48	sporadic
1996 October	0.38	0.058	0.068	+0.41	sporadic
1996 November	0.24	0.046	0.080	+0.43	poor correlation
1996 December	0.43	0.061	0.066	+0.04	sporadic
1997 June	0.60	0.038	0.039	−0.08	sporadic
1997 July	0.30	0.079	0.078	−0.07	sporadic
1997 September	0.44	0.115	0.127	+0.09	sporadic
1999 June	0.95	0.038	0.047	+0.27	
1999 July	0.92	0.038	0.048	+0.25	
1999 August	0.93	0.036	0.046	+0.24	
1999 September	0.94	0.045	0.056	+0.19	
1999 October	0.90	0.053	0.060	+0.10	
1999 November	0.89	0.038	0.046	+0.16	
1999 December	0.93	0.039	0.045	+0.10	
2000 March	0.69	0.089	0.110	+0.07	
2000 April	0.83	0.056	0.073	+0.30	
2000 May	0.66	0.061	0.125	+0.85	
2000 June	0.95	0.041	0.060	+0.46	
2000 July	0.90	0.027	0.044	+0.55	
2000 September	0.85	0.029	0.044	+0.44	
2000 October	0.88	0.043	0.060	+0.35	
2000 November	0.85	0.035	0.053	+0.44	
2000 December	0.78	0.080	0.101	+0.21	
1999 June–2000 December	0.91	0.043	0.054	+0.23	60 min medians
2001 April–May	0.97			−0.03	side-by-side comparison

Table 2: Integration Time Ratios

ν	$T_{\rm rec}$	a	b	τ_1	τ_2	t_1/t_2	
[GHz]	[K]					zenith	$A = 1.1$
220	55	—	—	0.045	0.036	1.1	1.1
345	83	3.65	-0.008	0.16	0.12	1.2	1.2
410	98	7.53	-0.017	0.32	0.25	1.4	1.4
492	118	23.6	$+0.19$	1.25	1.04	1.7	1.8
675	162	22.4	-0.02	0.99	0.79	1.7	1.8
691	166	26.4	-0.06	1.13	0.89	1.8	1.9
809	194	33.4	-0.03	1.47	1.17	2.0	2.2
875	210	24.2	0	1.09	0.87	1.7	1.8
922	221	72	$+0.02$	3.4	2.6	3.8	4.3
937	225	43.9	-0.02	1.96	1.56	2.4	2.6
1035	248	123	-0.8	4.7	3.6	9.3	11.6
1350	324	115	—	5.2	4.1	8.0	9.8
1500	360	101	—	4.5	3.6	6.2	7.5

Optical depth regressions $[\tau(\nu) = a(\nu)\,\tau_{220} + b(\nu)]$ from Matsushita et al. 2000. Other conditions: ALMA receiver goals, $T_{\rm rec} = 5h\nu/k$; median ambient air temperature at Chajnantor, $T_{\rm atm} = 270\,{\rm K}$; first quartile zenith optical depth at Chajnantor, $\tau_2(225\,{\rm GHz}) = 0.036$; typical normalized optical depth difference, $(\tau_1 - \tau_2)/\tau_2 = 0.25$; zenith and $A = 1.1$, which is the median for transit observations of uniformly distributed sources at $z < 60°$.

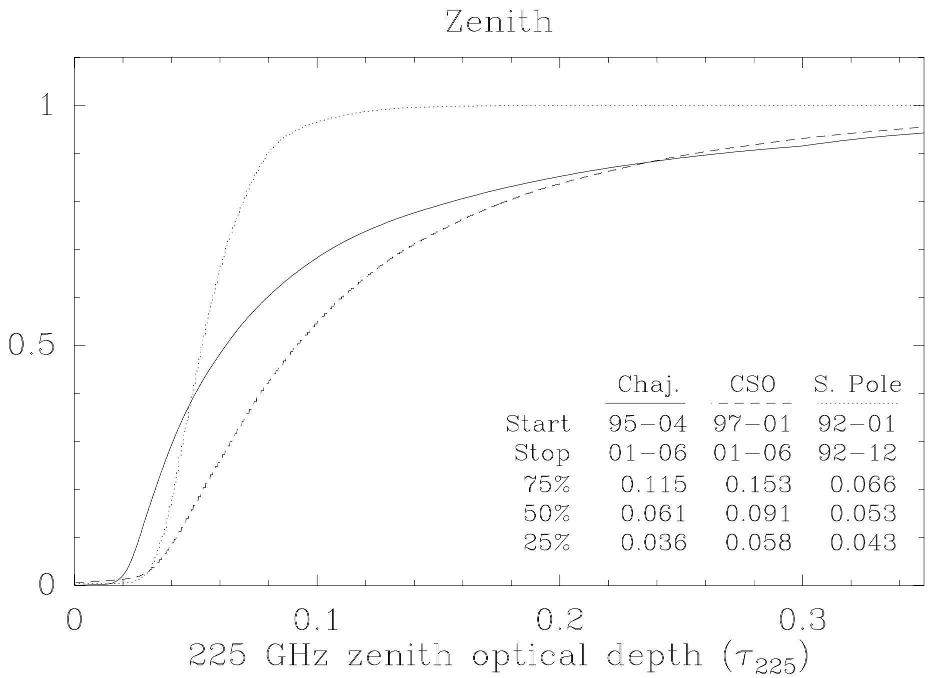

Figure 1: Cumulative distributions of the 225 GHz zenith optical depth (τ_{225}) measured at Chajnantor, at Mauna Kea (CSO), and at the South Pole (after Radford & Chamberlin 2000).

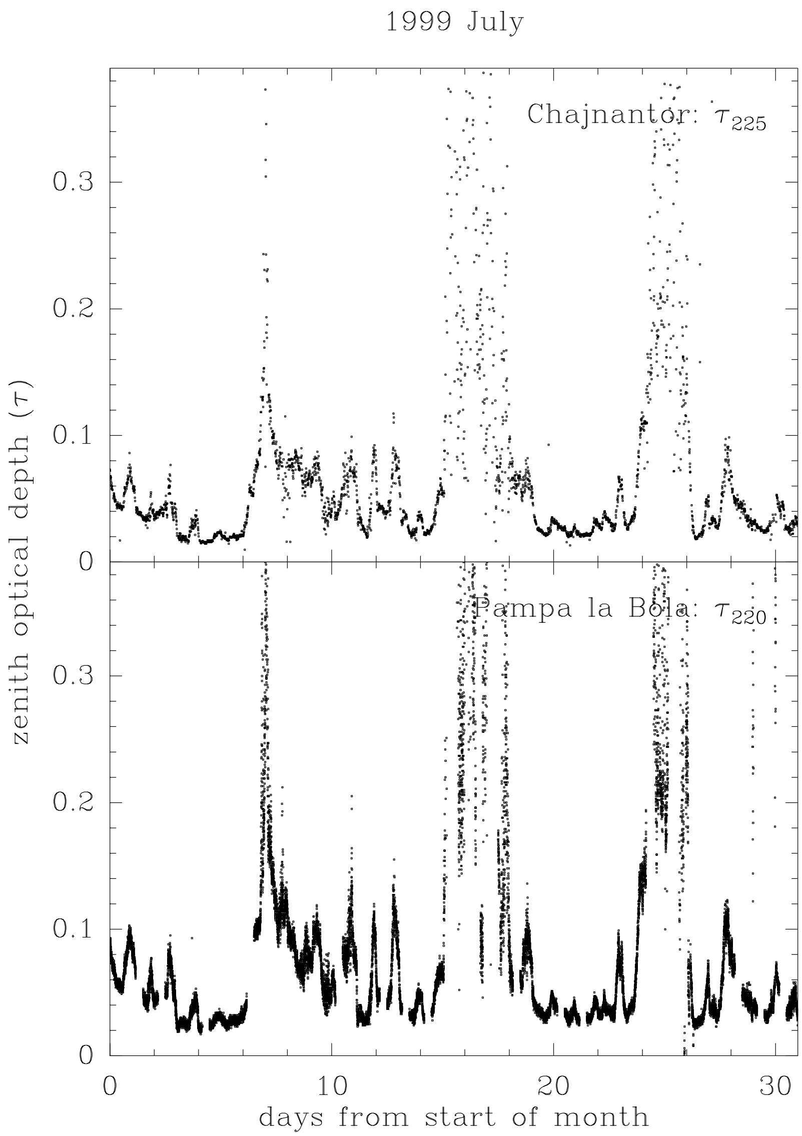

Figure 2: Zenith optical depth measured at Chajnantor (τ_{225}) and at Pampa la Bola (τ_{220}) during 1999 July.

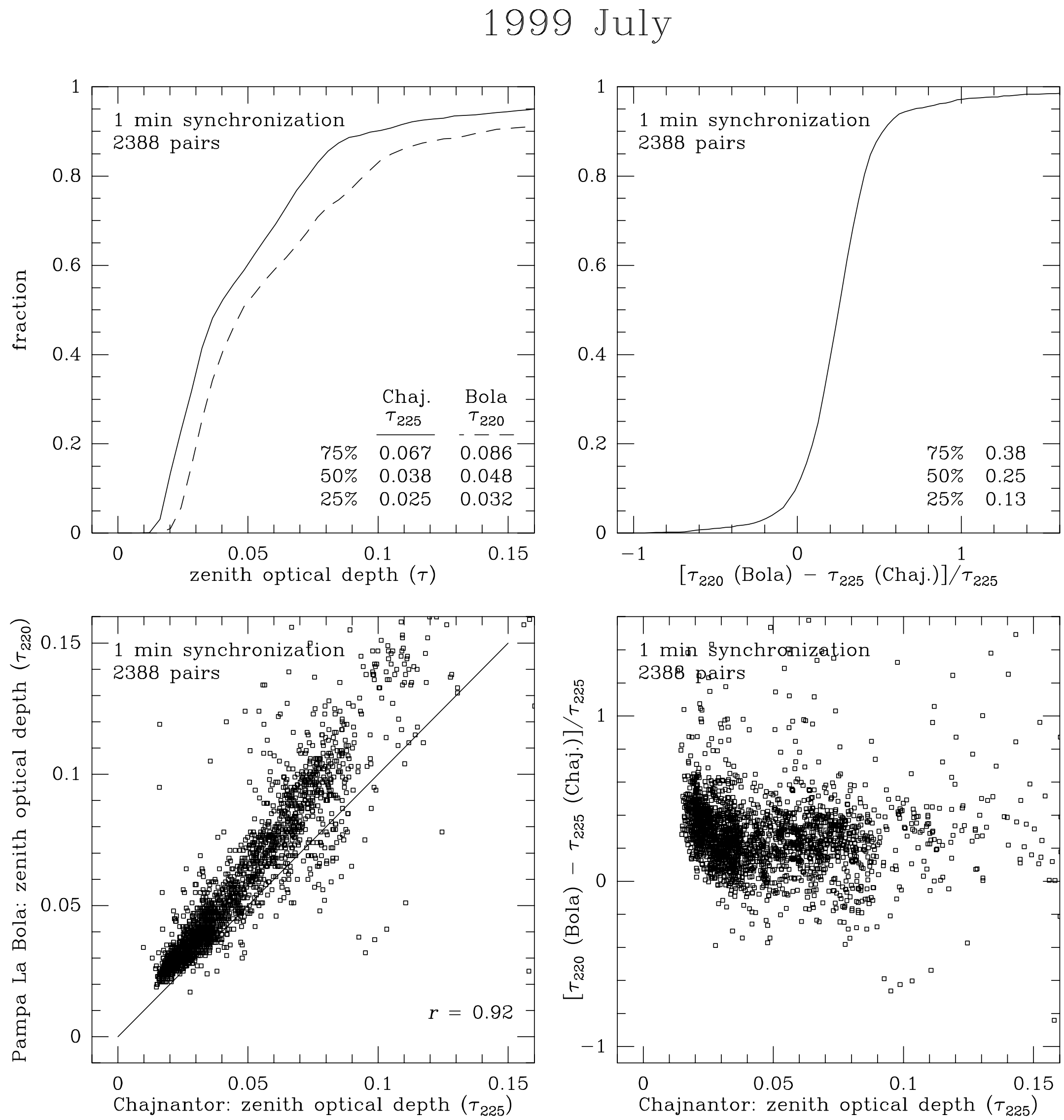

Figure 3: Time synchronized (paired) measurements of atmospheric transparency during 1999 July. *Left:* Cumulative distributions (*top*) and correlation (*bottom*) of zenith optical depths, τ_{225} (Chajnantor) and τ_{220} (Pampa la Bola). *Right:* Cumulative distribution (*top*) and correlation (*bottom*) of normalized differences, $[\tau_{220}(\mathrm{Bola}) - \tau_{225}(\mathrm{Chaj.})]/\tau_{225}$.

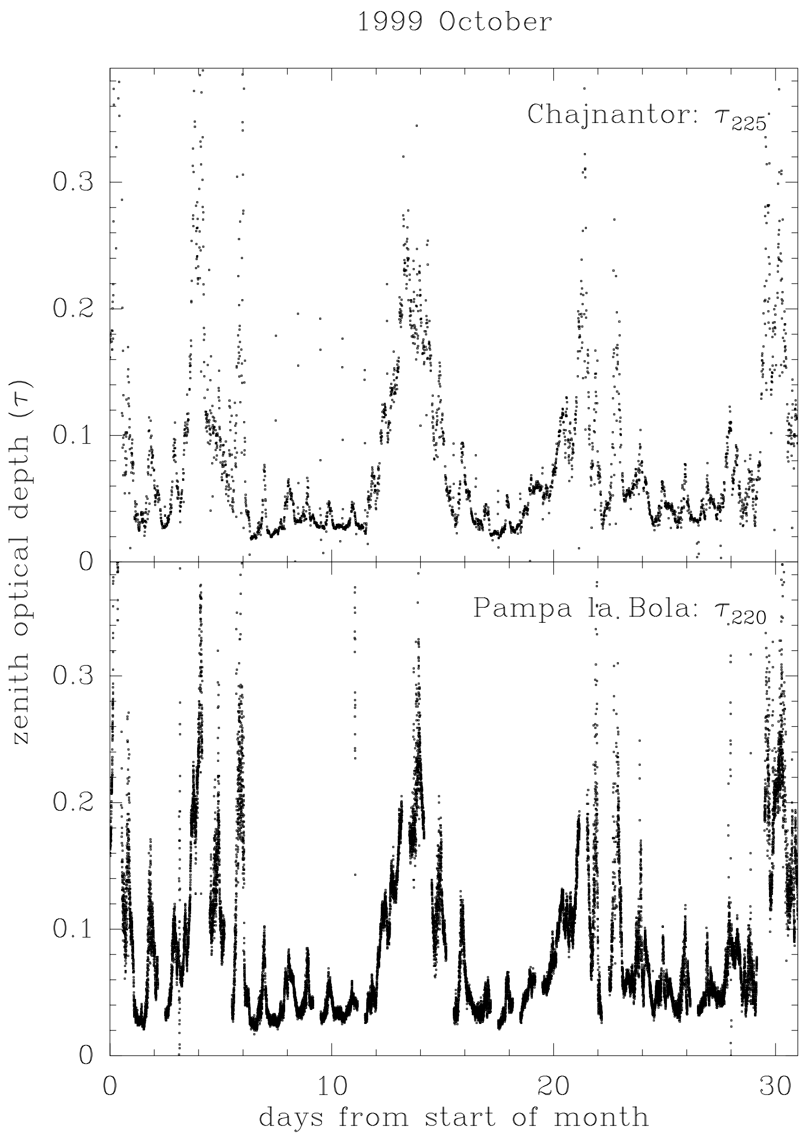

Figure 4: Zenith optical depth measured at Chajnantor (τ_{225}) and at Pampa la Bola (τ_{220}) during 1999 October.

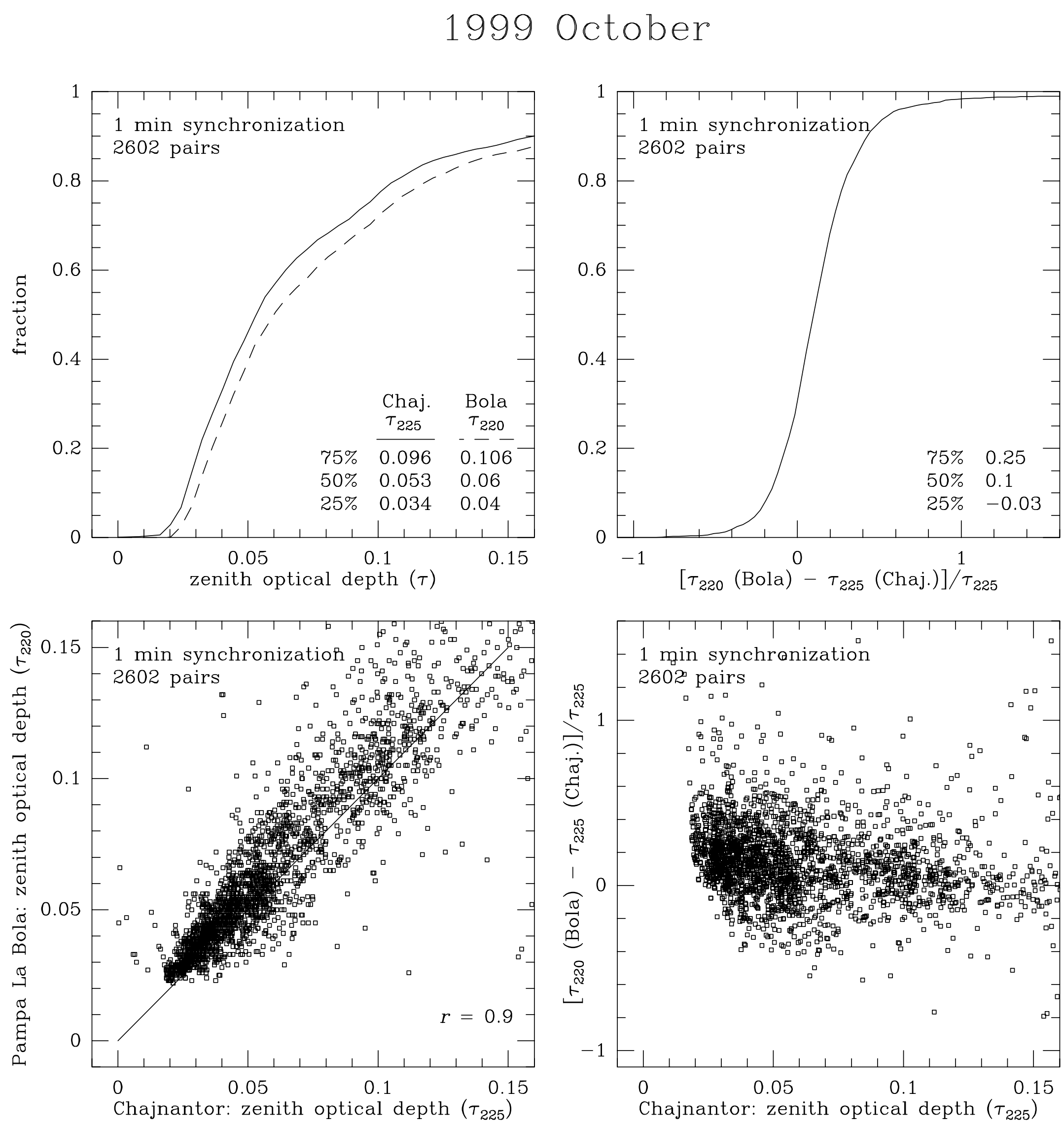

Figure 5: Time synchronized (paired) measurements of atmospheric transparency during 1999 October. *Left:* Cumulative distributions (*top*) and correlation (*bottom*) of zenith optical depths, τ_{225} (Chajnantor) and τ_{220} (Pampa la Bola). *Right:* Cumulative distribution (*top*) and correlation (*bottom*) of normalized differences, $[\tau_{220}(\mathrm{Bola}) - \tau_{225}(\mathrm{Chaj.})]/\tau_{225}$.

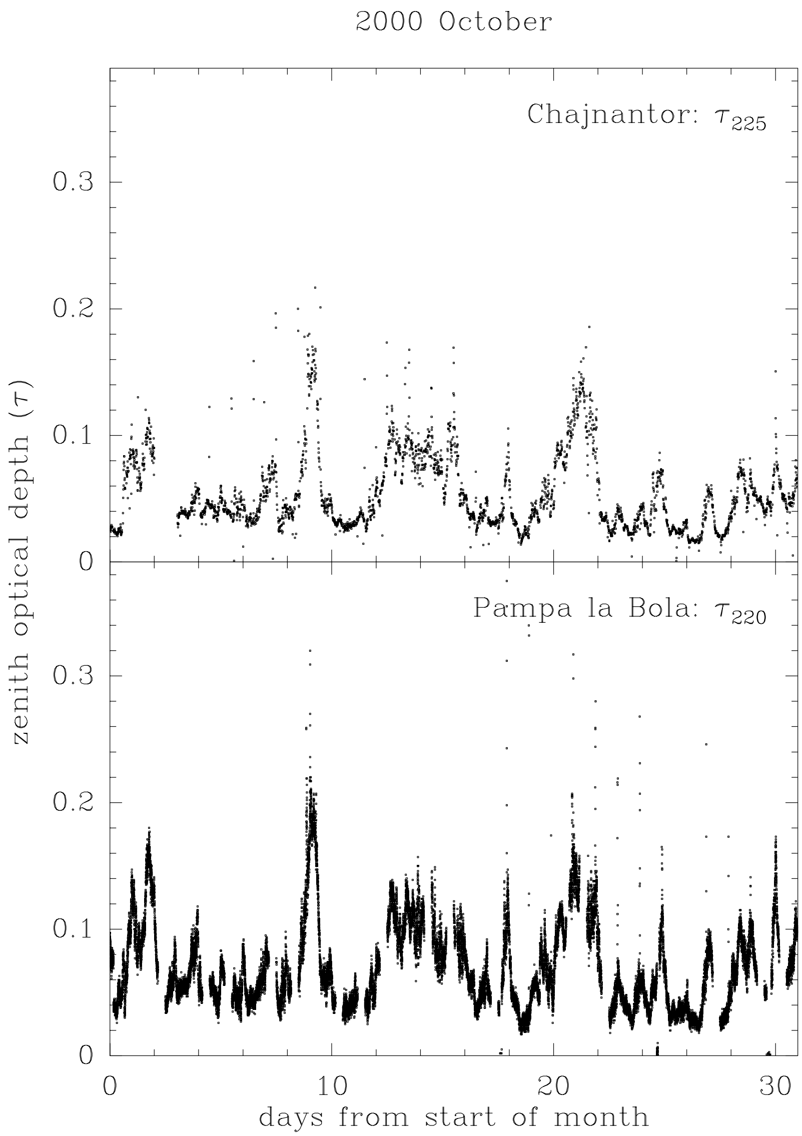

Figure 6: Zenith optical depth measured at Chajnantor (τ_{225}) and at Pampa la Bola (τ_{220}) during 2000 October.

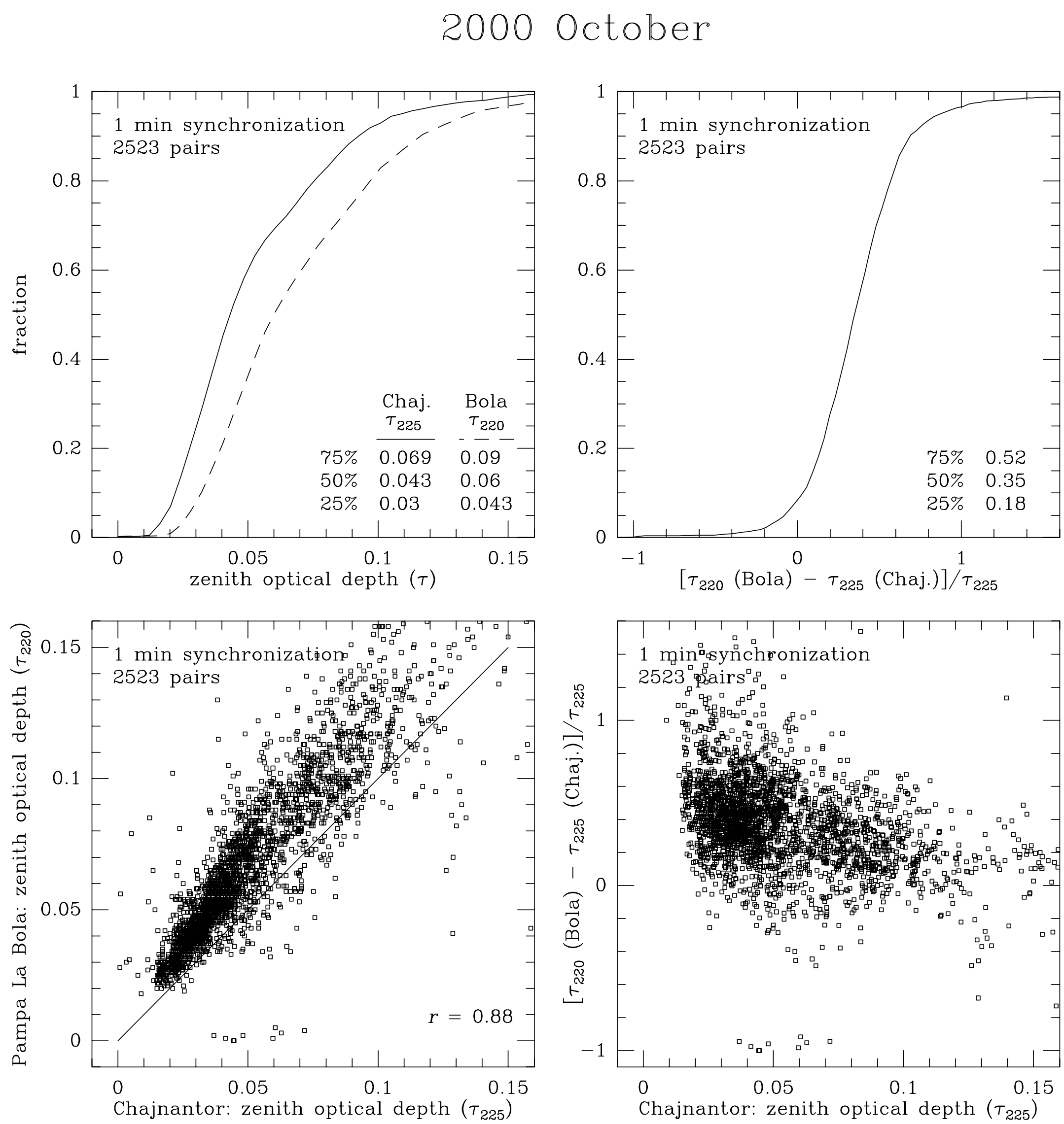

Figure 7: Time synchronized (paired) measurements of atmospheric transparency during 2000 October. *Left:* Cumulative distributions (*top*) and correlation (*bottom*) of zenith optical depths, τ_{225} (Chajnantor) and τ_{220} (Pampa la Bola). *Right:* Cumulative distribution (*top*) and correlation (*bottom*) of normalized differences, $[\tau_{220}(\mathrm{Bola}) - \tau_{225}(\mathrm{Chaj.})]/\tau_{225}$.

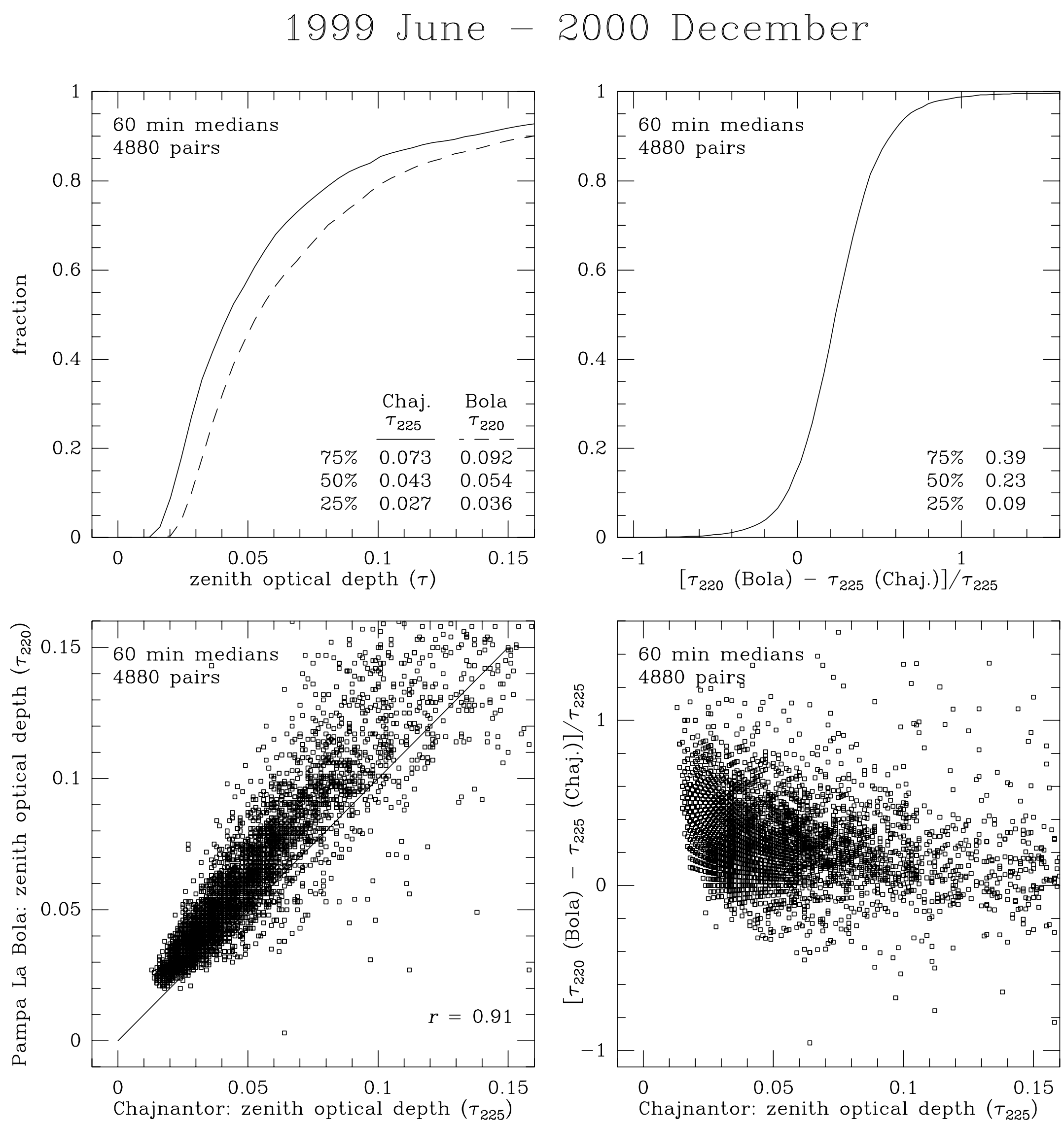

Figure 8: Hourly median measurements of atmospheric transparency for 1999 June through 2000 December. *Left:* Cumulative distributions (*top*) and correlation (*bottom*) of zenith optical depths, τ_{225} and τ_{220}. *Right:* Cumulative distribution (*top*) and correlation (*bottom*) of normalized differences, $(\tau_{220} - \tau_{225})/\tau_{225}$.

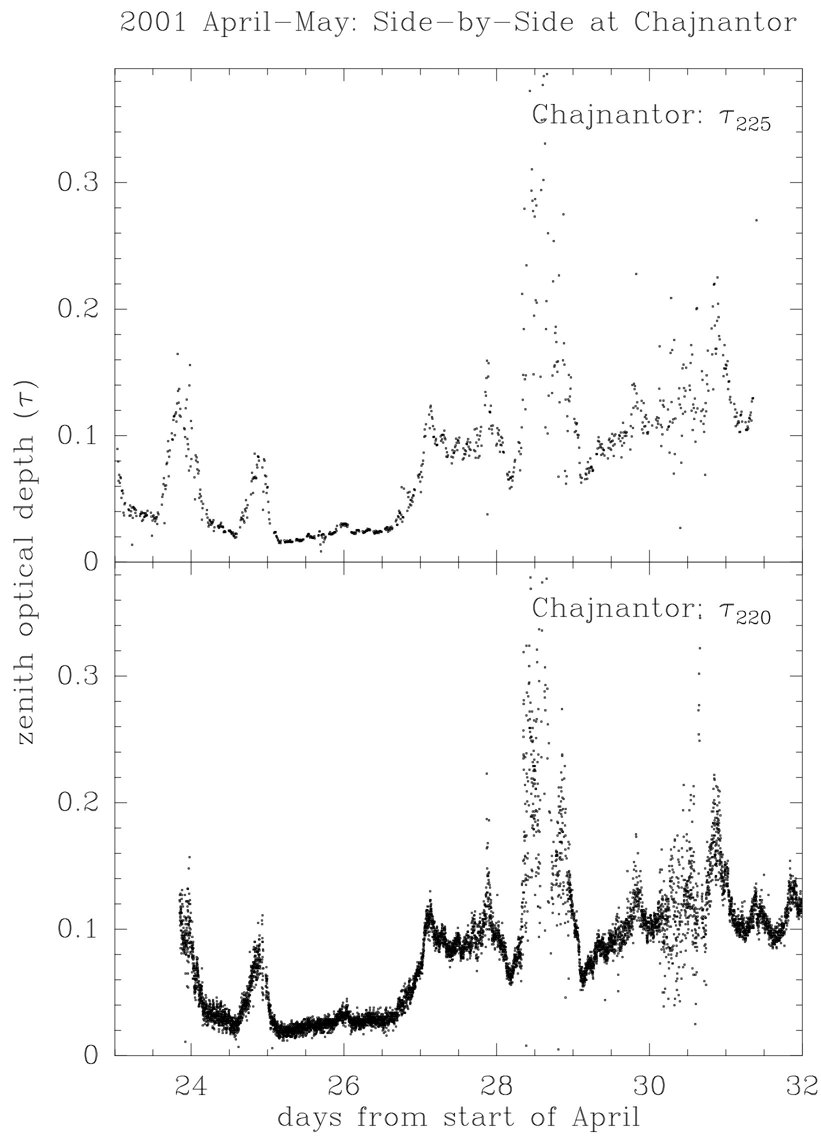

Figure 9: Zenith optical depth measured at 225 GHz (τ_{225}) and at 220 GHz (τ_{220}) during side-by-side comparison measurements at Chajnantor during 2001 April–May.

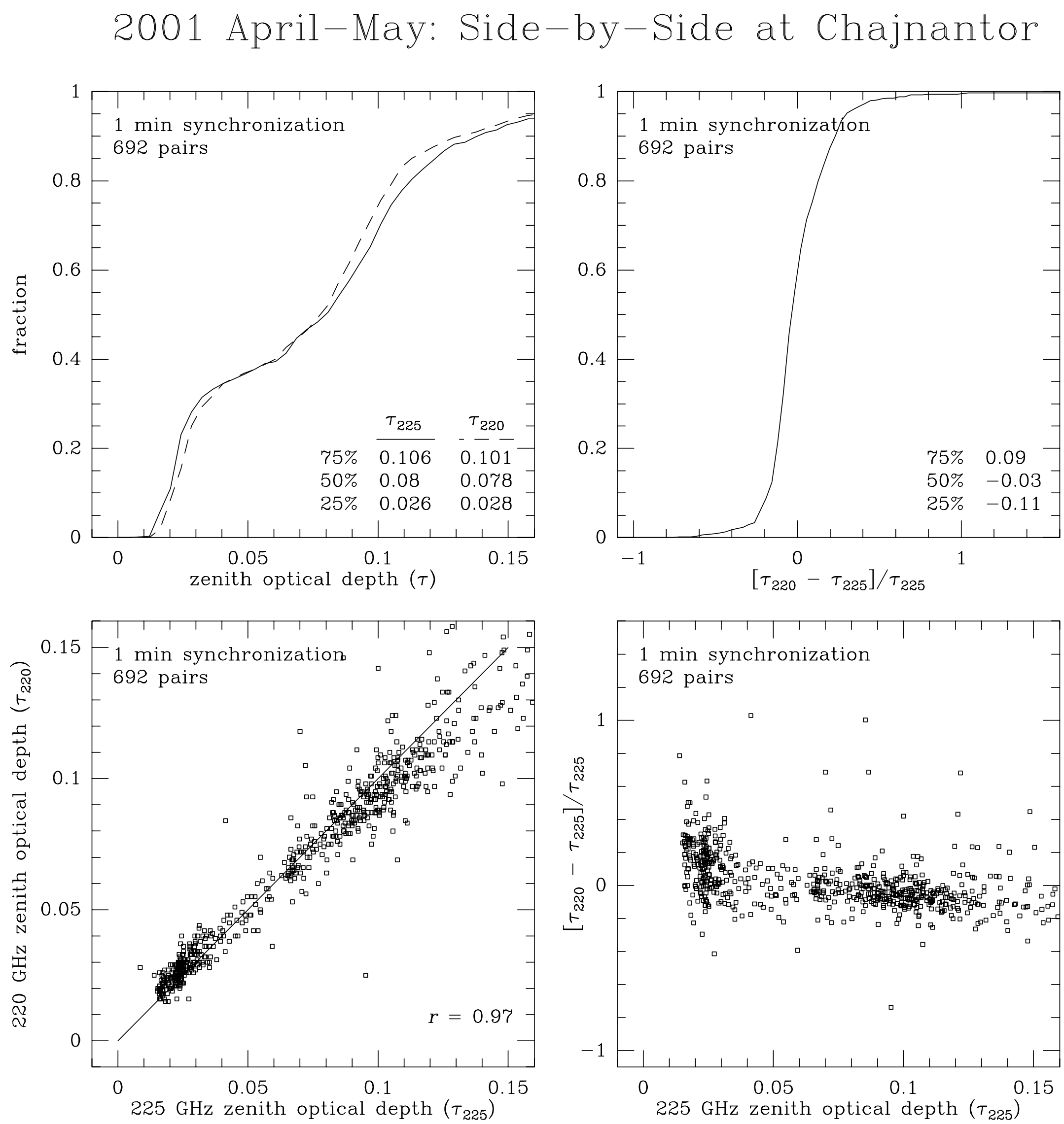

Figure 10: Time synchronized (paired) measurements of atmospheric transparency during side-by-side comparison measurements at Chajnantor during 2001 April–May. *Left:* Cumulative distributions (*top*) and correlation (*bottom*) of zenith optical depths, τ_{225} and τ_{220}. *Right:* Cumulative distribution (*top*) and correlation (*bottom*) of normalized differences, $(\tau_{220} - \tau_{225})/\tau_{225}$.