Characterization of Meditation EEG based on Consistency of Covariance Matrices over Time

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Abstract— **Electroencephalogram (EEG) is investigated for changes in the pattern of brain activity during meditation. Correlation between the neural activity in each region with those of other regions of the brain are studied. EEG recorded from fifteen practitioners of the peace and angelic meditations, being part of the Rajayoga meditation of Prajapita Brahmakumaris World Spiritual University is analyzed for this study. The mean and variance of the Frobenius norms of the difference matrices between the covariance matrices of successive epochs is used to study the meditative and non-meditative states. Analysis has been carried out region wise. The covariance matrices become more uniform during meditation, leading to decreased distance between matrices of successive epochs. The frontal region shows significantly decreased distances between the covariance matrices during meditation.**

Keywords— *EEG, Rajayoga meditation, peace meditation, angelic meditation, covariance matrices, Frobenius norm.*

I. INTRODUCTION

Meditation practice is considered to be one of the primary approaches in many mystical traditions to reach transpersonal states denoted by terms like samadhi, transcendental consciousness, and nirvana as reported by Britta et. al [1]. Conventional meditation teaching organizations stress the importance of regular practice, e.g. the yoga sutras of Patanjali (sutra I.14; Vivekananda, 2001 [2]). However, there are no objective indices to characterize the meditation of a long-term practitioner as "deep" compared to a novice.

Meditation can be considered as a family of attentional regulatory and complex emotional training regimes [3]. According to our survey of the existing literature, most of the work reported on the depth of meditation is based on the questionnaires as reported by Gifford-May et. al. [4], Piron et. al [5], Jian et. al. [6] and Tetsuya et. al [7]. A recent study of Sharma et. al [8] on seed stage meditation under Rajayoga practice with open eyes reported activation of many networks across delta and low alpha frequencies. Sharma et.al [9] saw higher band power in alpha and theta frequencies and high frontal and parietal cortical asymmetry in long term Rajayoga meditators. Telles et. al [10] reported increase in heart rate during Rajayoga meditation practice which is a sign of psychophysiological arousal due to cardiosympathetic activation. However, a decrease in heart rate was also reported along with decrease in respiratory rate, systolic and diastolic blood pressure during Rajayoga practice by Sukhsohale et. al. [11]. The study suggested that cardiovascular parameters improved because of sympathetic arousal. Decrease in peak latency of a negative component in the middle latency auditory evoked potentials during Rajayoga meditation was seen in a study by Telles et. al [12]. Neuroimaging study conducted by Sharma et. al [13] on long-term meditators of Rajayoga meditation suggested enhanced white matter integrity in corpus callosum segments as compared to controls. Increased entropy of EEG time series in frontal lobe during Rajayoga practice were observed in the dataset analyzed in the current work [14]. Our work intends to be the starting point in quantifying the depth of meditation and developing an index for the same using the covariance matrices. In this work, we analyse the EEG recorded during Rajayoga meditation, which is practiced with the eyes open, which makes it unique among the different meditation techniques. An attempt is made to analyse the covariance matrix which captures the inter-dependencies of different regions of the brain during the meditative states. Features such as the mean and variance of the distances between the successive covariance matrices have been used to compare the meditative with the non-meditative states.

II. DATASET DESCRIPTION

A. Subject Selection

EEG data collected from fifteen healthy right-handed subjects [15] practicing Rajayoga meditation regularly for a period of more than 10 years (age 30-52 years, mean 43.9 (SD=3.96) years) has been used in this study. With a record of regular practice, these meditators have spent 11-17 years in practicing this technique after learning the same. At the time of recording the EEG data, the total number of hours spent in meditation throughout their life `ranged from 4000 to 7200 hours. The subjects did not have any history of cardiac, pulmonary, and other nervous system dysfunctions. The experimental procedures were explained to the subjects. A written information consent was obtained from each subject. The status of non-consumption of alcohol, cigarette or any therapeutics by the subjects within the last six months was confirmed.

B. Experimental Protocol

EEG data was recorded using 64-channel ANT Neuro amplifier with a 10-10 Waveguard standard 64-channel cap. EEG signals were digitally filtered at 0.5-75 Hz during recording. The subjects were asked to sit on a floor mat, and it was made sure that the ground was not in contact with the body during the entire recording session.

3 minutes Baseline (BL) was recorded, and the subjects were asked to relax with their eyes open before the recording of the meditation session. After BL, the peaceful soul consciousness (PM) state of meditation was practiced and recorded for around 10 minutes. PM is defined to be focusing their attention on the positive thought considering themselves as peaceful souls. PM was followed by an intermediate baseline (IBL) for 3 minutes. Following IBL, subjects were asked to practice another technique, angelic (AM) state of meditation for 10 minutes, where subjects assumed to attain a blissful state. A final baseline (FBL) was recorded for 3

minutes. The complete protocol is presented graphically in Fig 1. The fundamental difference between the two meditation techniques is the self-observing experience in PM and the state of being detached from the physical body, its sensual pleasures, relationships, and material assets in AM [16] More information on different states of meditation is given in Appendix.
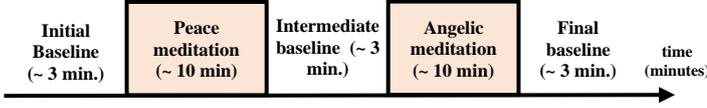

Fig. 1. The protocol followed in EEG recording: Subject practice two types of meditation for 10 min. each. Baseline EEG is recorded for 3 min. at the beginning, in between the two meditative states and at the end.

C. Preprocesing

The data was recorded at a sampling frequency of 1024 Hz. Using EEGLAB v 13.4 the pre-processing pipeline was performed. Line noise (50 Hz) removal followed by band-pass filter with cut-off 0.5 Hz to 45 Hz was applied on the EEG time series. The runica independent component analysis algorithm [17] was applied to reject eye movement and muscle activity. Residual components with eye movements, muscle artifacts and electrode popping were removed to make the data artifact-free using a manual procedure. 14 subjects were considered for analysis and one subject was dropped due to excessive artifacts and low SNR channels. Data of each subject is grouped into five broader groups namely Frontal, Frontocentral, Centroparietal, Occipital and Temporal (see Fig. 2). Both Temporal right and left are grouped as Temporal.
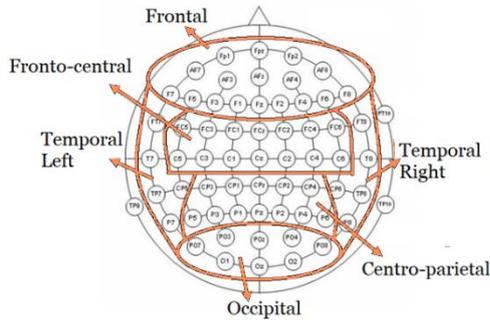

Fig. 2. 64-channel EEG electrode configuration following the 10-10 system. The electrodes from broad regions are grouped for the proposed analysis.

III. METHODOLOGY

Covariance matrix characterizes the relationship between various random variables. Covariance matrix obtained from EEG signals of different channels quantifies the pairwise correlation between those channels over a given epoch [18]. The diagonal elements of the covariance matrix give the variances of the different channels being analyzed. The off-diagonal elements capture the inter-channel correlation. In the work reported here, the covariance matrix is computed for a set of channels grouped as a specific region of the brain. In our proposed work, distances between the covariance matrices of successive epochs are used to distinguish between the different meditative and non-meditative (baseline) states. During meditation, the interchannel correlation is expected to

increase in certain lobes of the brain, which we expect the sequence of covariance matrices to capture and illustrate. Further, since attention is maintained in a particular way throughout any meditation session, we also expect the correlation pattern to be relatively stable across successive epochs and have minimal changes in time.
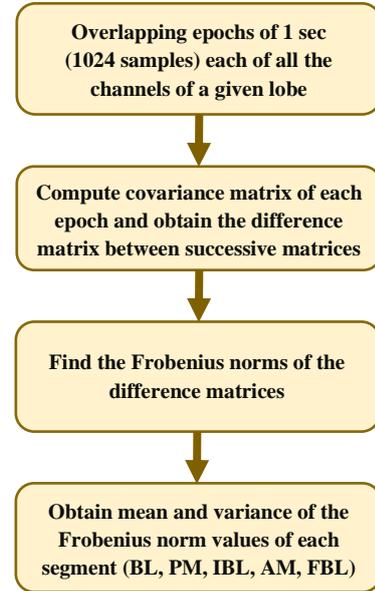

Fig. 3. Graphical abstract of the proposed methodology. Overlapping epochs of 1024 samples each were extracted from all the channels and covariance matrices were calculated across the channels. Distance between successive covariance matrices was calculated using the Frobenius norm of the difference matrix. Mean and variance of the Frobenius norm values were calculated for all the segments.

A. Covariance matrix of a group of channels

Figure 3 shows the graphical abstract of the proposed methodology to characterize the meditative states. All the channels of a given lobe are considered for obtaining the covariance matrix for that lobe. The artifact-free multichannel EEG of ith lobe is divided into overlapping epochs of 1 sec each with 50% overlap between the epochs. The data matrix X_i^k for the k-th epoch of the i-th lobe is formed as

$$X_i^k = \begin{bmatrix} x_{1,1} & x_{1,2} & .... & x_{1,N} \\ x_{2,1} & x_{2,2} & .... & x_{2,N} \\ : & : & .... & : \\ : & : & .... & : \\ x_{M_i,1} & x_{M_i,2} & .... & x_{M_i,N} \end{bmatrix}, \quad \begin{cases} 1 \le i \le 5 \\ 1 \le k \le K_j \end{cases}$$

where, M_i is the number of channels in the i-th lobe, N is the number of samples per epoch, and K_j is the number of epochs for the j-th state of meditation or baseline namely BL, PM, IBL, AM, FBL and $1 \le j \le 5$. The covariance matrix is defined as

$$C_i^k = \frac{1}{N} X_i^k (X_i^k)^T - \mu_i^k (\mu_i^k)^T \qquad (1)$$

where μ_i^k is the mean column vector of the k-th epoch. Difference matrices between the covariance matrices corresponding to successive epochs are obtained. The (k-1)th difference matrix D_i^{k-1} is given by,

$$D_i^{k-1} = C_i^k - C_i^{k-1}, \quad \begin{cases} 1 \le i \le 5 \\ 2 \le k \le K_i \end{cases} \qquad (2)$$

Frobenius norms of the difference matrices are calculated for all the epochs.
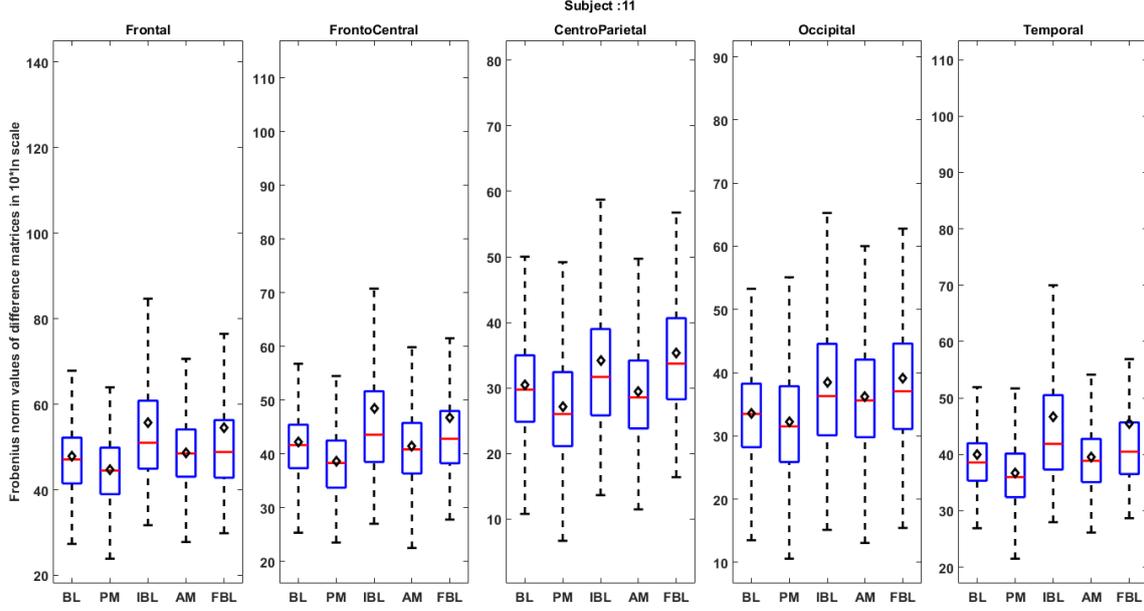
Fig. 4. Box plots of the Frobenius norms of difference matrices between covariance matrices of successive epochs for subject 11 without the outliers. Red lines represent the median and diamonds, the mean. (A) Frontal region, (B) Frontocentral region, (C) Centroparietal region, (D) Occipital region, (E) Temporal region.

The Frobenius norm of the difference matrix D_i^k is obtained as,

$$h_i^{\ k} = \sqrt{trace[(D_i^k)' \ D_i^k]}, \begin{cases} 1 \le i \le 5 \\ 1 \le k \le K_j - 1 \end{cases} \quad (3)$$

resulting in a vector of length equal to $K_j - 1$ for the data corresponding to each state (BL, PM, IBL, AM, FBL).

B. Mean and variance of the sequence of Frobenius norm values

After estimating the Frobenius norm values ($h_i^{\ k}$), the mean and variance for a given lobe and subject are obtained as,

$$H_{mean}^i = mean(h_i^{\ k}), \begin{cases} 1 \le i \le 5 \\ 1 \le k \le K_j - 1 \end{cases} \quad (4)$$

$$H_{var}^i = var(h_i^{\ k}), \begin{cases} 1 \le i \le 5 \\ 1 \le k \le K_j - 1 \end{cases} \quad (5)$$

IV. RESULTS

The analysis of the covariance matrices for consistency during the different states showed decrease in the mean and variance of the norms of the difference matrices during the meditation states from their values during the non-meditating states. Figure 4 shows the distance values during meditating and non-meditating states in all the regions of the brain for subject 11 considered in the analysis.

Our hypothesis in analyzing the covariance matrices is decreased values and variance of the distances between the covariance matrices in the meditative states as compared to non-meditative states. This is the trend seen in all the lobes with varied statistical significance as given in Fig 6. However, the mean distances during meditating states were also observed as given in Fig 5. Changes in the distance values in

the frontal region were more statistically significant than in other regions and hence the statistical significance results of the frontal region only are reported here. A study conducted by Travis et. al [19] has reported increase in frontal EEG coherence and was positively correlated with inner orientation, emotional stability and moral reasoning. The higher statistical significance in frontal lobe as compared to other lobes to be investigated in future.

Given that very few antecedents of scientific papers investigating the covariance matrices and in specific the distance between the covariance matrices during meditation, comparing the results reported in the proposed work is difficult. The meditation types studied here are practiced with open eyes, whereas almost all the other traditions are performed with closed eyes. Also, the neuronal activity during meditation is confounded by many factors and hence the results may not be consistent with other meditation methods. The non-parametric Wilcoxon tests revealed that the proposed Frobenius distance values decreased in the frontal lobe during the meditative states as shown by the z-values given in Table I and p-values in Table II.

TABLE I. z-values of mean distances between covariance matrices of successive epochs from the frontal lobe. Comparison of the meditation and baseline (non-meditating) states.

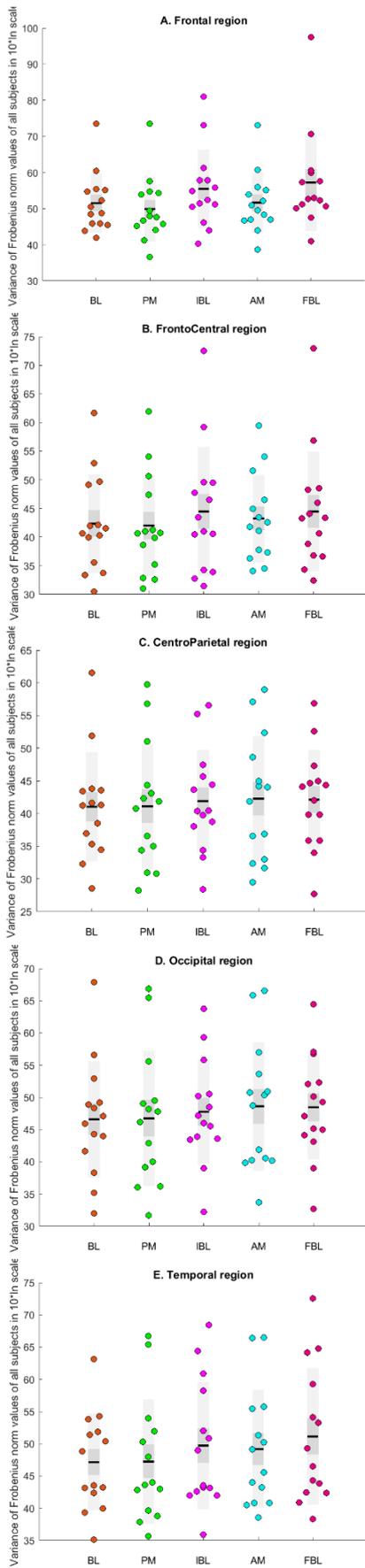|	**PM**	**IBL**	**AM**	**FBL**
BL	-2.3541	-1.9147	-0.2825	-2.4797
PM		-2.9191	-2.2286	-1.9147
IBL			-2.103	-1.3497
AM				-2.2286

Fig. 5. Univariate scatter plot of the means for all the meditative and non-meditative states of all the 14 subjects. Black horizontal line represents the mean, dark grey box, the SEM and light grey box, the standard deviation. (A) Frontal region, (B) Frontocentral region, (C) Centroparietal region, (D) Occipital region, (E) Temporal region.
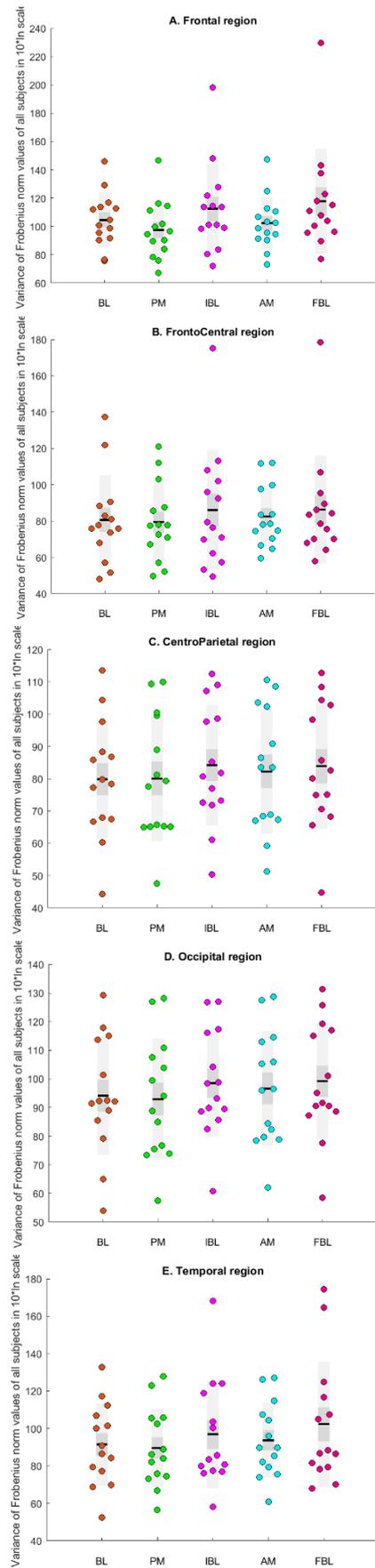
Fig. 6. Univariate scatter plot of the variances for all the meditative and non-meditative states of all the subjects (14 points in each state). Black horizontal line represents the mean, dark grey box, the SEM and light grey box, the standard deviation. (A) Frontal region, (B) Frontocentral region, (C) Centroparietal region, (D) Occipital region, (E) Temporal region.

TABLE II. p-values of mean distances between covariance matrices of successive epochs from the frontal lobe. Comparison of the meditation and baseline (non-meditating) states.

	PM	IBL	AM	FBL
BL	0.0094	0.0281	0.3897	0.0066
PM		0.0018	0.0129	0.0281
IBL			0.0179	0.0885
AM				0.0129

V. Conclusion

In summary, peace and angelic meditations, practices under the tradition of Rajayoga meditation, resulted in decreased mean and variance of distance values between covariance matrices of successive epochs of the EEG recorded from the frontal region of the brain. This shows that the interrelationships between the frontal lobe channels are becoming much more uniform during meditation, compared to the baseline. This consistency of EEG covariances can be used to quantify the depth of meditation in addition to the questionnaires resulting in an index for the same.

Our study provides an example of using covariance matrices in characterizing and distinguishing between meditative and non-meditative states. Future research should include the analysis of frequency band-wise covariance matrices and address how these stationary covariance patterns are related to the long-term positive effects that certain meditative traditions can have on mental and physical health. Other important direction should include the quantification of depth of meditation based on EEG.

Acknowledgment

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The content of this section is taken from [20]. First step in Brahmakumaris Rajayoga meditation (BKRYM) is to become soul conscious. The question is however, have you really experienced yourself to be a soul and have you been able to sustain this experience? Visualization helps to create and sustain this consciousness. For better visualization, inculcating the thoughts, self-talk may help. Following are some thoughts which helps in visualizing the soul consciousness stage which is the fundamental of all the states such as peaceful soul consciousness state, angelic state etc.

A. Soul consciousness state

"I turn my thoughts inward... I pay no attention to the things around me…. I direct all my thoughts towards the one whom I really am... I ask myself: Who am l?... I am a soul….an eternal, immortal soul.., l, the soul, will always live.,. I am the living being... the spark of living energy in the center of the forehead...I realize that this is the one whom I really am,,. for so long I have thought that I was the body, my form, my role.,. but now I know that I am an eternal soul and that my form is a point of light.
l, the soul, shine like a star... like a bright star in the center of the forehead...I visualize myself... I see myself as this shining star of living light.., my attention is focused on point of light.

B. Peaceful soul consciousness state

For visualization of peaceful soul state, one will undergo the process of contemplating following thoughts.

"What are the original qualities of l, the soul?...my original quality is of pure divine peace...peace is my original nature-.-the closer I get to myself, the deeper I go into my original peace...peace, my original strength. I am no longer distracted by the things around me.. peace and silenced. Peace is such a great power, the power of my true self...the power to best able under all conditions...I allow this feeling of pure peace...the peace of my original nature to flow through me...peace belongs to me...peace is me...and when I am close to my real self, I notice how strong I am... I have strength,.. the power to be myself whenever I want; beyond influences...I am completely inside...very quiet; Very peaceful...at one with myself,. Peace and silence.
In silence I experience a feeling of love., love for who I really am... understanding of myself..-acceptance of myself... respect for my original eternal being... when I see myself in this way, love emerges,., and confidence..,and I ask myself: the world of eternal peace...the world of light.,. of silence.-.the world beyond of stillness and peace...this is my silent,

eternal home...this is where I come from... the world of silent peace and light...peace and light." "Where do I come from?... I realize that my original home is far, very tar away from this world of sound and matter... it is

C. Angelic state

Angelic state is an advanced state of BKRYM where the soul consciousness is the primary stage and proceeds with meeting the Shiv Baba; the supreme soul (used many times in the text).

"My ability to help others is often limited by time and distance and can reach only a few people at a time. Subtle help through sending thoughts of virtue, support and good wishes can benefit all souls, even those who are physically many miles away.
God's love and support are eternal gifts that are given to all souls. I can be an instrument to pass this spiritual nourishment on to others. When connected with God I stay peaceful, loving, happy and pure and can refresh many others with the power of good wishes."

"I fly to my home...the world of pure light...the world of peace...here in this peaceful land I sit next to the source of peace, God the Supreme... the unlimited Ocean of Peace.
In front of me I now visualize   all other souls...like so many stars...I share all the peace and love I feel within me with these souls...I am filled with this powerful vibration of purity coming from God...passing through me...to all others.

A superb sensation of light grows inside me as I take on my angelic form...I become the form of light...and I am aware of Baba... God, the Supreme...the Ocean of Light.
My sweet Baba ...You are the World Benefactor...and, when I am with You...so too am I a benefactor to others.
I bathe gently in these warm waves of love and peace...which I now pass on these experiences to all my brother souls...and in this light and detached state...I can see the beginning...the middle...and the final scenes of this cycle of world history unfolding before me...I can see the time of transformation...of great beneficial change...coming close.
Here, in this region where only angels can dwell...I am light and free...absolutely no physical or subtle burden can pull me...I enjoy only the bliss of Your sweet love. I feel your purity. Baba what is left for me but to become an instrument for your mercy...
The old tired world is so far away...and yet close enough that our pure vibrations and thoughts can bring love, solace and mercy to all...my dearest Baba...may all souls come to taste this sweet nectar of contentment!"