[EN-029] Fluctuation Scaling in the Air Traffic Controller Communication Activities

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Abstract: In this paper we report the phenomenon of fluctuation scaling in air traffic controller communication activities. Taylor's power law has long been observed in a wide range of disciplines, ranging from ecology through physics to social science, to characterize the fluctuation scaling of the system. In ATM system, which is a typical human-centered system, controller communication activities play a vital role in system's safety and efficiency. We analyze controller communication activities from a complex system point of view: ATCOSIM controller communication data has been analyzed with a human dynamics approach and the result shows that the variance of the controller's communication activities has a linear relationship with the average of the activities, which can also be described as Taylor's power law with the exponent $\alpha = 1$. The ensemble fluctuation scaling found here may help a better understanding the dynamics of ATM system, so that to close the gap between the physical part and human part of ATM complex system.

Keywords: human factors; air traffic controller; fluctuation scaling; Taylor's power law

1. INTRODUCTION

Air Traffic Management (ATM) system has been progressed with the introduction of new technologies together with the enhancements from the methods employed by the operators, the air transport system has significantly improved its capability, safety and efficiency. But how to meet the continuous growth of traffic demand however is still an urgent and practical task being faced by the researchers and the engineers of the field. The technologies and the methodologies not only improve the system capability but also increase the system complexity. Large number of parts of the system being interconnected keeps the structure of the whole system unportrayable. Prediction and control of the system is quite difficult due to the linear or non-linear interaction between the elements. For instance, although the local sector behavior may be clear, the global picture of the system could be still unknown. The understanding of the mechanism by which the ATM system evolves has becoming the central question of this field.

Modeling the ATM system from a complex system approach may be an efficient way to analyze the whole system and the subsystems. The air traffic controller is the main human part of the system, whose behavior has direct influence on the system performance. As an important part of the ATM system, air traffic controller has been long well studied . Efforts have been made into the understanding of the workload and taskload of the controllers. Although workload metric is widely used in many ATC centers to describe the mental cost of the controller to accomplish the ATC tasks, it is still unable to be predicted due to its unknown dynamic property [1]. In ATM system, voice communication was the primary means used by controller, to control air traffic prior to the emerging of digital data communication between controller and aircraft, i.e. Controller Pilot Data Link Communication (CPDLC). However, it is still the only channel for information flow between pilots and controllers in most control centers. Under such circumstance, controller voice communications activities still have direct impact on the whole system evolution. In the past, communication events were extensively used to measure workload [2-4]. We assume that the communication activity encapsulates both cognitive efforts and physical efforts of the controllers to accomplish the mission of ensuring traffic safety and efficiency. Therefore, the analysis of the controller communication activities is of great importance.

One may think that it is impossible to develop a general model of controllers communications due to the unique sector structure, the dynamical changed traffic, and the individual knowledge and experience. Our analysis here presents that the intellectual challenge could be the physical understanding of the rules by which the air traffic controller control the traffic. A few qualitative mechanisms used by the controller to mitigate cognitive complexity have been found in [5]. In the other fields, the quantitative study of human has discovered amazing results on human activities. Instead of the presumed randomly occurred human actions, there is increasing evidences showing that there exist similar activity patterns among human daily activities, including human correspondences [6], email communication [7], human printing behavior [8], and online films rating[9], and human mobility [10]. These findings suggest that there is a universal law that governs human activities[11].

Besides the human system, the Taylor's power law has been observed in many natural and human-driven systems, ranging from ecology system through stock market to human dynamics, characterizing the fluctuation scaling property of the system. The Taylor's power law is named after L. R. Taylor in recognition of his paper in 1961 [12]. Taylor's law can be applied to describe many complex systems in characterizing the relationship between the fluctuation in the activity of an element and the average activity. The relationship is usually in the following from:

$$fluctuation \approx const. \times average^{\alpha}\text{, where } \alpha \in [1/2, 1]$$

Based on the data over which the averages are taken, the Taylor's power law can be grouped into two categories: Temporal Fluctuation Scaling (TFS) and Ensemble Fluctuation Scaling (EFS) [13]. Models for the explanation of the origins of Taylor's power laws can be found in [14], in this paper we report the ensemble fluctuation scaling in the controller's communication activity.

The rest of the paper is organized as following: Section 2 gives a description of the communication data on which we have investigated, followed with the method with which we manipulate the data. Section 3 shows the empirical results of the ensemble fluctuation scaling in the controller communication activities. Possible explanation of the phenomena is also discussed. The paper ends with conclusion remarks in Section 4.

2. METHOD

2.1 Controller's communication data

The controller communication data used in this study is from the ATCOSIM Air Traffic Control Simulation Speech corpus of EUROCONTROL Experimental Centre. The aim of the ATCOSIM is to provide a speech database of non-prompted and clean ATC operator speech. It consists of ten hours communication data, which were recorded during ATC real-time simulations[15]. These simulations were conducted between 20/01/1997 and 14/02/1997, with the aim to evaluate the concept of RVSM (reduced Vertical Separation Minimum) in Europe. For the purpose of ATCOSIM, only controllers' voice was recorded and analyzed. Considering the traffic initialization phase with little speech, the first half-hour of traffic was not recorded. Hence, each record consists of circa one hour of communication data. Both speech signal data and transcription of the utterance, together with the complete annotation and meta-data for all utterances, can be found in the database. Because the simulations took place more than ten years ago, it is impossible to find the information on traffic and airspace corresponding to the communication data.

The general information of the whole fifty exercises is shown in table 1. We still have the detailed information on each exercise, while it is not given here.

Table 1 Information on the 50 exercises in the ATCOSIM database

	TOTAL	AVERAGE
Length of the exercise (hh:mm:ss)	59:18:37	1:11:10
Number of the flights (*complete flights**) identified in the exercise	3121 (1966)	62.42 (40)
Number of the communication events (Unidentified) in the exercise	10078 (1276)	201.56 (26)

**Complete flight* is the flight that receives both *hand-in* message and *hand-out* message.

2.2 Definition

Communication activity is defined as the event that controller press the push-to-talk button and hold in order to send the transmissions to aircraft, disregarding the contents of the transmissions. Particularly, each utterance in the ATCOSIM data is a single communication event representing a complete communication activity. Empty transmission is also seen as the complete communication activity.

The purpose of this paper is to examine the ensemble fluctuation scaling in the controller communication activities. One may naturally relate the communication activities to the traffic activities. A flight will receive at least two messages (hand in and hand out) from the controller when it traverses the sector. The more flights enter the sector, the more communication activities should be. Of course, communication activities will fluctuate according to the traffic situation. We simplify *traffic activity* here as the cumulative number of the flights entering the sector. The more communication activities are made, the more fluctuation should be.

2.3 Data processing

In order to correlate the communication activities and traffic activities, it is essential to acquire the traffic information associated with the communication data. According to the regulation of controller-pilot voice communication, both the flight call-sign and the types of the communication could be identified based on the analysis of the content of the speech data. Unidentified communication events are labeled with empty flight number. Two important types of the communication are also identified: *hand-in* and *hand-out*. The *hand-in* communication to the flight indicates that and this time the flight enters the sector, while the *hand-out* communication gives the time of the flight leaves the sector. Flights with both hand in communication and hand out communication are the complete flights. There is around 10% of the communication events are labeled with empty flight number.

In order to illustrate the procedure of the calculation of the communication activities, we first define the following terms.

F : Set of the flights that have entered the sector.

L^f : List of the flight call-signs decoded from the communication events. The call-signs are arranged in exactly the same order as the communication events. It should be mentioned that empty flight call-sign has also been included.

C : Set of the cumulative number of the communication events. It has the same size as F . $C(i)$ is the number of communication events when there have been i flights entered the sector.

m : The number of the flights in F .

q : The cumulative number of the communication events;

We then present in Fig. 1the skeleton of the algorithm for the computation of the number of the communication events associated with the number of the flights have entered the sector in each exercise.

Step 1. Set the start point s and the end point e .

$$m = 0,\quad q = 0.\quad F = \varnothing$$

Step 2. Calculate m and C based on the time sequence of the flight call-sign.

FOR i=s : e

IF $L^f(i) \neq \varnothing \, \&\& L^f(i) \notin F$

$m = m + 1;$

$q = q + 1;$

$F = F \cup \{L^f(i)\};$

IF $m > 1$,

$C(m-1) = q;$

END;

ELSE

$q = q + 1;$

END;

$i = i + 1;$

END

$C(m) = q$

Step 3. Output the result.

Fig. 1. The scheme for the computation of the number of the communication events and the number of the flights entered the sector.

3. EFS in ATCO communication

3.1 Ensemble Fluctuation Scaling

We note that each exercise consists of different amount of the traffic. The minimum number of the flights in the exercises is 44 in the exercise GM2_01, while the maximum number of the flights is 73 in ZF2_05. In order to calculate the mean and the standard deviation of the communication activities, we set the exercise start time as the start point and the algorithm will terminate when the number of the flights reaches 44. In the Fig. 2, we show the empirical results on the number of the communication activities with the number of the flights. As can be seen from the figure, both the average and the standard deviation of the communication activities grow quickly as the number of the flights increases.

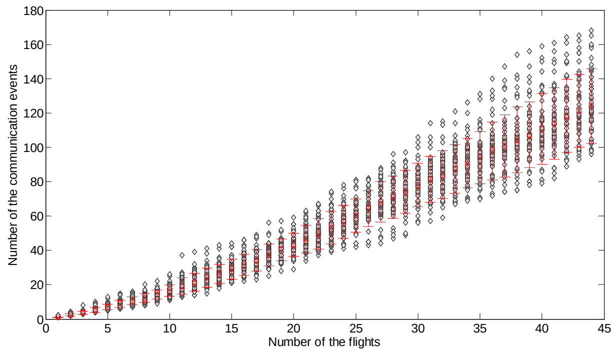

Fig. 2. Results on the number of the communication activities associated with the number of the flights have entered the sector (50 exercises). Each marker stands for the cumulative number of the communication activities correspond to the number of the flights. Errorbar shows the average of the number of the communication activities and the standard deviation of the data.

We then plot the standard deviation according to the average of the communication activities in the Fig. 3 (a). Solid line is the linear fit of the empirical data. The residual shown below indicates the linear fitting is applausive. Hence, the standard deviation of the activities and the average activities has a clear Taylor's power low relationship with $\alpha = 1$.

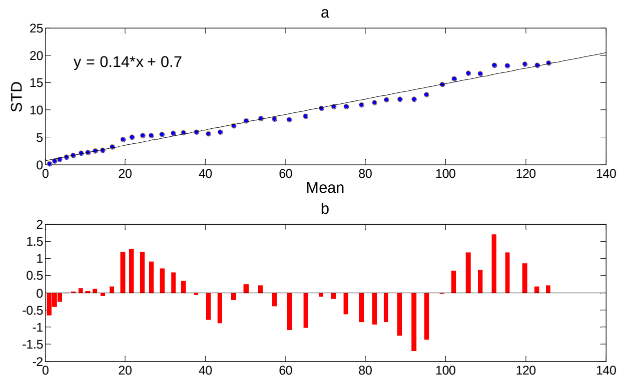

Fig. 3. Empirical results of the fluctuation scaling in the communication activities.

3.2 EFS and communication activities distribution

If we know the statistical characteristic of the communication activities on each flight, then it will be easier to formulate the reasonable explanation of the origins of the EFS in the communication activities.

Hence, following the last paper [16] we study the distribution of the number of communication events of each flight. The percentages of the flights as the function of the numbers of communication events in each exercise are plotted in the Fig. 4.

While we were expecting that the curves of each line could be collapsed into a single one, however, the unknown airspace configuration and the traffic distribution make it impossible to scale the obtained results. The shapes of the curves differ from each other (see “All the 50 Exercises”). According to the horizontal position of the climax of the curve, we classify all the 50 exercises into three groups: Group 1, Group 2, and Group 3. After categorization, the curves in the same group vary similarly. The difference between the shapes of the curves in three groups may result from the different types of the sectors simulated: en route sectors, approach sectors, and the approach sectors with flying over route. More information is needed to formulate the distribution function of the communication events and to explain its association with the EFS found in this paper.

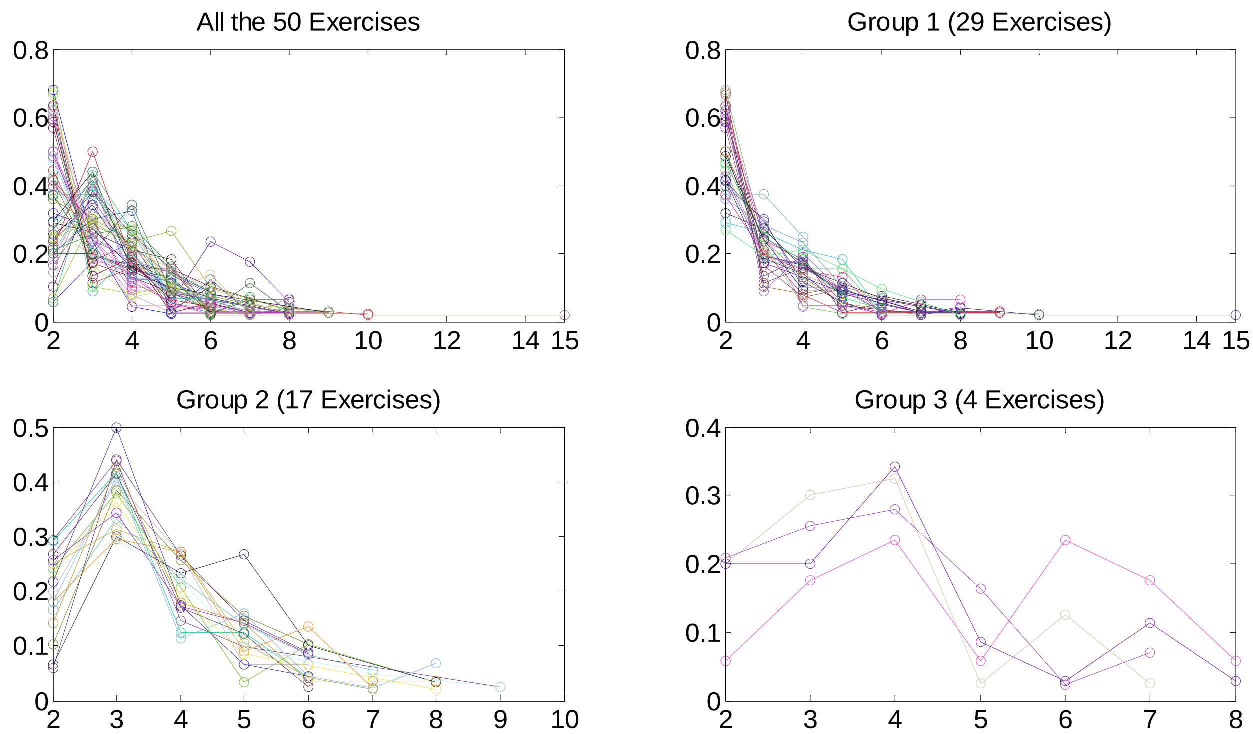

Fig. 4. The percentages of the flights as the functions of the numbers of messages received by the flight (complete flights). Vertical axis is the percentage of the number of the flights, while the horizontal axis is the number of the communication events involved by the flight. Different colored maker stands for the different exercise.

4. CONCLUSION

The analysis from ATCOSIM data shows that with the increasing number of flights entering sector, both the mean and the variance of the controller communication activities grow, with a power law ($\alpha = 1$) relationship between the two quantities. Validation will be made by the use of other simulation or operation data before the claim of the Taylor's power law in the controller communication activities.

In a recent paper, the authors propose the universal mechanism underlying the Taylor's law observed in different scientific disciplines. They show that the law results from the density of state function characterizing the considered system [14]. If the validation of the EFS in the controller communication activities from the other simulation or operation data is acceptable, then it will be of great value to investigate the mechanism behind the phenomenon.

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