Accepted Manuscript

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PII: S0273-1177(17)30547-1
DOI: http://dx.doi.org/10.1016/j.asr.2017.07.037
Reference: JASR 13347

To appear in: *Advances in Space Research*

Received Date: 13 March 2017
Revised Date: 24 July 2017
Accepted Date: 25 July 2017

Please cite this article as: Mayorova, V., Grishko, D., Leonov, V., NEW EDUCATIONAL TOOLS TO ENCOURAGE HIGH-SCHOOL STUDENTS' ACTIVITY IN STEM, *Advances in Space Research* (2017), doi: http://dx.doi.org/10.1016/j.asr.2017.07.037

NEW EDUCATIONAL TOOLS TO ENCOURAGE HIGH-SCHOOL STUDENTS' ACTIVITY IN STEM

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Many students have to choose their future profession during their last years in the high school and therefore to choose a university where they will get proper education. That choice may define their professional life for many years ahead or probably for the rest of their lives.

Bauman Moscow State Technical University conducts various events to introduce future professions to high-school students. Such activity helps them to pick specialization in line with their interests and motivates them to study key scientific subjects.

The paper focuses on newly developed educational tools to encourage high school students' interest in STEM disciplines. These tools include laboratory courses developed in the fields of physics, information technologies and mathematics. The paper demonstrates examples of various laboratory courses developed by authors. More than 2000 high school students already participated in this experimental courses. These activities are aimed at increasing the quality of STEM disciplines learning which will result in higher quality of training of future engineers.

INTRODUCTION

Education in the sphere of scientific disciplines is a foundation in training of experts for high-tech industries. Because of that many countries – such as Australia, China, UK, Israel, South Korea, Singapore and USA – currently implement state-funded STEM programs - Science, Technology, Engineering, Mathematics [1,2,3]. In Russia, such STEM centers have been opened at several universities, centers of technical support of education, and techno-parks, in cooperation with businesses, e.g. with support from Intel. Such centers represent a network of research laboratories that support scientific, technological and engineering input into auxiliary educational programs of high-school students. This project is aimed to increase interest among high-school students towards engineering and technical majors and to motivate senior students to continue education in scientific and technological fields. STEM laboratories make modern equipment and innovative programs more accessible for children who are interested in research activity[1].

One of the directions in modernizing Russian secondary education system is setting various profiles – specializations in education – which has to meet the educational needs of students, reach the goals of person-specific education, and raise the level of achievement of scientific disciplines [2]. Introduction of specialized education in modern high-school makes it possible to select individual education trajectory, while profiled education allows a student to familiarize themselves with chosen profession.

One of the problems in modern school during the modernization period is lack of strong inter-disciplinary connections. Often a student who is quite successful in one discipline cannot utilize received knowledge neither in real life, nor in other disciplines. The main reason is in secondary education attention is paid to acquisition of knowledge whilst the later stage of development in our society is to prepare a graduate to use such knowledge in real-life situations. Because of this it is very important to make a transition of competency education into high schools. The introduction of profiled education into high school requires a change in social requirements, developing new approaches, new content, new forms and methods and also new educational methods of teaching high-school disciplines of scientific nature [4,5].

I. ANALYSIS OF THE PROBLEM AND POSSIBLE SOLUTION

Bauman Moscow State Technical University conducts various events to introduce future professions to high-school students. Here are some examples of such events:

[1] http://stemcentre.ru/

[2] http://government.ru/media/files/mlorxfXbbCk.pdf

- Open Doors, when departments of the University are shown to high school students and they are briefed on specialization of various departments and possible future career paths;
- Scientific-Technical Olympiads, which allow the selection of gifted students from all over Russia and offer them seats in the University without further exams;
- Various joint exercises, lectures and laboratory activities.

Practice shows that in order for high school students to better acquire knowledge in science fields there is a need to implement educational tools, which strengthen inter-disciplinary connections [6, 7]. The main goal of strengthening such connections is to raise the quality of the knowledge and skills by deeper understanding of existing connections in nature and in society. In order to reach that goal first and foremost it is important to integrate scientific knowledge into theoretical research and practical experiences in high school. Integration (from Latin Intergratio – restoration, replenishment) is a process of uniting and connection between disciplines, a condition of connection of several parts into one unit, and also a process leading to such condition. The Main goal of integration is to create a unified understanding of the surrounding world, i.e. to form a worldview. Integration in a broader meaning is viewed in education not only from the point of interconnection between disciplines, but also as integration of technologies, methods and educational forms. Integration allows the development of a scientific style of thinking, allows to broadly applying a scientific method of learning, form in students generic notions in geography, biology, mathematics, chemistry, natural science, forms extra-disciplinary knowledge and skills.

Nowadays a "project method" is being introduced in the world for integration of knowledge. Such approach leads to a more interested, personally-significant and thoughtful acquisition of knowledge, which increases motivation and active participation of students in the educational process. Each project-oriented task represents a tight chain of linked actions for students. This allows them to view the project-identify problems in various modes of activity, which naturally requires integration of knowledge. In such a way modern education, as a method of learning about the world, will ensure integration of subjects and various methods of gaining knowledge[3] about the world and will increase the creative potential of a person for open and thoughtful actions, for holistic and open understanding and appreciation of the surrounding world [8, 9, 10].

However there are at least two issues, which complicate integration of education in standard classes and laboratory activity of a high school:

1. The competency of a teacher, who requires a full understanding of multi disciplines which may be beyond their ability and scope of understanding
2. The required laboratory equipment and adequate production facilities which may be missing in the school.

Forming of a certain direction of a personality requires building of a content of scientific education based on integration principles, using system approach and taking into account person's capabilities. Such activity can be realized in various ways:

- solving specially developed tasks/researches, structured in such a way so that they direct thinking process of a student in certain direction;
- working with separate educational modules, connected with studied topic, which allow to broaden the knowledge of a studied topic;
- learning additional approaches and methods of solving a task;
- implementing projects in which several activities are integrated – thinking over and studying of a set task, representing of a material in adequate format, reporting to their piers on the results of the research.

Thus, new forms of activity, which have not been used prior for the classes in mathematics, physics or geography are now included into some existing technologies. For example – experiments and practical activity when studying arithmetic, geometry, probability and statistics; during running these topics some group activities are also implemented, useful communication skills are developed[4]. Practical educational experience reveals lack of geometric or spatial imagination among modern high-school students. Unfortunately, majority of modern graduates sometimes lack even basic geometric imagination. It is possible to form such geometric imagination most successfully during mathematic laboratory activity, using some basic shapes as learning material and visual aids, as well as other non-traditional but useful shapes. Academician A.N. Kolmogorov paid

[3] http://festival.1september.ru/articles/610404/

[4] http://www.itmathrepetitor.ru/l-d-kudryavcev-o-sushhnosti-matematiki/

serious attention to laboratory activity while teaching mathematics[5].

II. ALGORYTHM OF CREATING NEW EDUCATION TOOLS

In modern conditions high schools, which have ties with universities, have additional capabilities to expand science education by having open access to new resources – ideas, information, knowledge, programs, methodologies and technological equipment. Currently main components of infrastructure used for research activity are Centers of Collective Use (CCU), Scientific-Educational Centers (SEC) and infrastructure of Departmental Laboratories (DL). Each of such components is to solve the tasks at the level of their competency. Centers of Collective Use are usually formed at leading scientific centers, academic institutes and several universities.

Fig 1. Ground station “Polus” to receive satellite sensing data. Bauman University Youth Space Centre

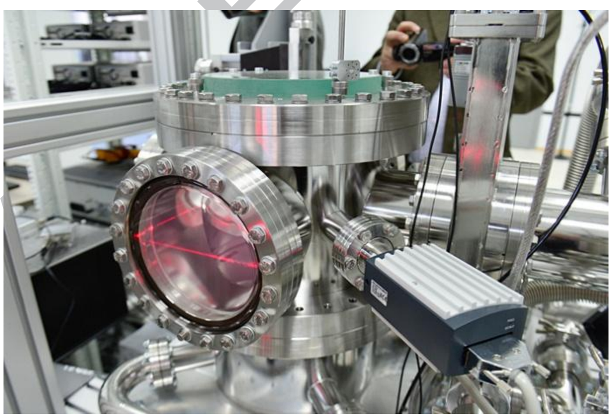

Fig 2. Bauman University Ion & Plasma Technologies Scientific-Educational Centre equipment

They possess unique equipment and are aimed to conducting fundamental breakthrough research, preparing experts of highest qualification. Scientific-Educational Centers are usually created at the basis of universities, with participation of industrial and business partners, and are equipped with serial-production experimental equipment [Fig. 1, 2]. Their main task is not only support of scientific and research activity of youth but also organization of cooperation between researches and scientists of various generations, effective introduction of young people into engineering creative work, creation of conditions for training of professionally-oriented, scientifically trained, intellectually-developed young generation[6].

Ability to work in research-and-development laboratories of universities allows high school students to learn the methodologies of conducting scientific experiments, conduct the experiments themselves, process the results. Basis and algorithm of developing new educational tools is a sequence: High-School – COC/SEC/DL – Information Resources – Knowledge – Industrial Base.

As an example, we would like to show organizational structure of research and professional-orientation activity for high school students at the basis of SEC’s and research laboratories of Bauman Moscow State Technical University (BMSTU). Bauman University has 15 Scientific-Educational Centers. Some of them are: “Ion & Plasma Technologies”, “New Materials, Composite Materials, Nano-technologies”, “Photonics and infra-red technologies”, “Techno-park of Information Technologies”, “Hydronautics”, “Youth Space Centre” and others. Special practical activities with demonstration of how to use the knowledge received in high-school are prepared and being conducted for high schools which have partnership relationships with Bauman University [Fig. 3- a),b),c)].

Youth Space Centre SEC has developed a set of new educational tools – laboratory activities for senior high-school students.

[5] http://www.nano-obr.ru/file.php/1/metod_material/mgtu/mgtu.07-08.pdf

[6] http://us.dogm.mos.ru/51/12554.html?view=event

Fig 3-a),b),c). Laboratory activities for senior high-school students in Bauman University Youth Space Centre

III. EXAMPLES OF NEW EDUCATIONAL TOOLS FOR HIGH-SCHOOL STUDENTS (10-11 grades)

New educational tools – laboratory activities and methodical materials – have the ability to practically demonstrate several effects and phenomena using the equipment of Mission Control Centre for microsatellites at Bauman University.

Laboratory activity No 1 studies Doppler Effect by analyzing the change of frequency of radio signal coming from a satellite to ground station. Source of a signal is an actual satellite. Laboratory equipment is a guided antenna, receiver and information display system.

Orbitron software is used to perform this laboratory activity. This application is used to calculate satellite's position on orbit and gives guidance to Earth-based antennas. Main application window shows Earth map, satellite's trajectory, orbital parameters and some velocity characteristics, area of satellite's radio-visibility, calculated times of radio communication, position of ground tracking station, radio equipment parameters and orientation of antennas. It is possible to simulate all these data for any date/time. At each moment of time it is possible to receive information on satellite's velocity and receiving frequency taking into account Doppler Effect [Fig. 4].

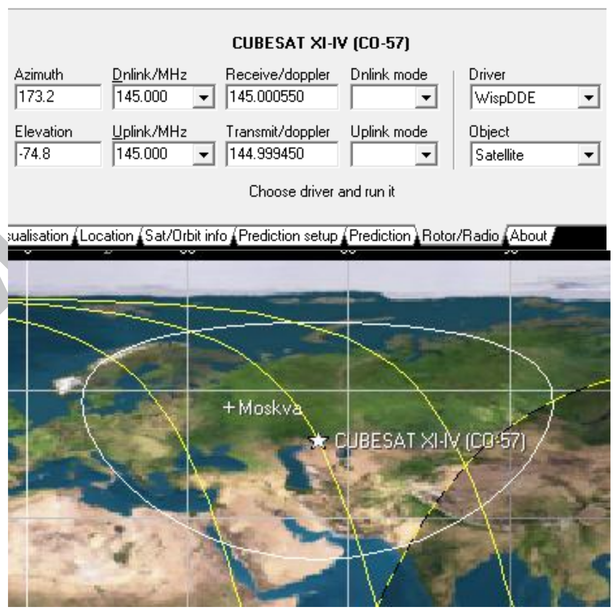

Fig. 4. Orbitron application used to control radio antenna

Participants of this activity study the dynamics of frequency change; calculate related kinematic characteristics of satellite's motion.

The first step is to draw the graph of function $\Delta f = f - f_0$ vs. time (f – frequency of received signal, f_0 – frequency emitted by satellite). This graph has a shape in general similar to function $y(x) = -\arctan(x)$. At first the frequency of received signal f is higher than frequency f_0, then the value of f is constantly decreasing so that at certain point (approximately at the highest point of the trajectory in reference to ground station) it is equal to f_0, and then continues to decrease. The graph of $\Delta f(t)$ received by school students is symmetrical with center of symmetry being the point on the graph where initial frequency is equal to received frequency.

Next stage – explanation of behavior of function $f(t)$. Received frequency is related to emitted frequency as in this formula:

$$f = f_0 \cdot \frac{\sqrt{1-\frac{V^2}{c^2}}}{1+\frac{V}{c}\cdot\cos\theta} \qquad (1)$$

where V - velocity of the signal source in relation to receiver (observer), θ - angle between direction to emitter and velocity vector in coordinate system tied to receiver.

Formula 1 uses absolute value of emitter's relative velocity vector, however high school students will face difficulties in calculating this vector. Absolute velocity of receiver (for Bauman University – a point on the surface of the Earth with ≈ 56 degrees latitude) can be calculated by multiplying angular velocity of rotating Earth ω_3 by the distance to rotation axis at this latitude [Fig. 5]:

$$\mathrm{V}_{Moscow} = \omega_{\mathrm{E}} \cdot \mathrm{R}_{\mathrm{E}} \cdot \cos 56° = \frac{2\pi}{86400} \cdot 6371 \cdot \cos 56° = 0.259\ \mathrm{km/sec}.$$

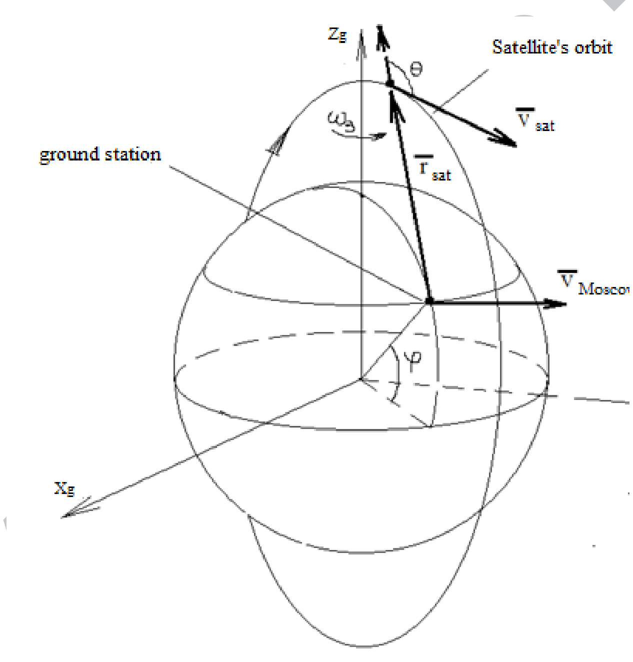

Fig. 5. Relative position of spacecraft and ground station

Velocity of the source, a satellite, in this task is close to 7.5 km/sec (satellite's height is 700 km above the Earth, the orbit is near-circular). So, velocity of the receiver is approximately 29 times lower than velocity of the source signal. Since radio communication window for a satellite is approximately 15 min long, it is possible to assume that the velocity of receiver is zero, and then θ - is the angle between vector to the satellite and satellite's absolute velocity. By inserting values of frequency and satellite's velocity into formula (1) it is possible to define θ(t) at any point in time very close to real orbital motion. When a satellite enters the zone of radio communication reachable from ground station, this angle is always larger than 90°, then it will decrease to certain smaller angle by the time a satellite disappears over the horizon. This defines the shape of $\Delta f(t)$, which was observed in the first part of this laboratory activity.

Laboratory Activity No 2 studies atmosphere drag acting on a body thrown at an angle in gravitational field.

That's a math laboratory activity which does not require any special laboratory equipment, just calculating tools and software which are available at Bauman University Mission Control Centre.

This laboratory activity consists of two parts. In first part students study the basics of MathCAD tool, define trajectory parameters without drag influence. All formulae describing such trajectory have already been studied by them as part of standard high-school curriculum, so they can assess the correctness of received results. In second part students study the motion in atmosphere, with main task to find optimal throw angle, which will result in farthest distance, and to define trajectory parameters. This is material they have not studied in school, including solving sets of differential equations. Because of that they are working with pre-set equations:

$$\begin{cases} x(t) = x_0 + \frac{mV_{x0}}{\mu}\left(1 - e^{-\frac{\mu}{m}t}\right), \\ (t) = \ {}_0 + \frac{mV_{y0}}{\mu} + \frac{m^2 g}{\mu^2} - \frac{mg}{\mu}t - \frac{m}{\mu}\left(V_{y0} + \frac{mg}{\mu}\right)e^{-\frac{\mu}{m}t}. \end{cases}$$

where x_0, y_0 – coordinates of the point from which the body is thrown, V_{x0}, V_{y0} – x and y projections of initial velocity vector, t – time, m – mass, μ – aerodynamic drag coefficient, g – G-force acceleration.

In order to simplify the task, it is solved by graphical method using students' skills which they have obtained in first part. Graph of relationship of $y(t)$ from $x(t)$ is drawn first, where time is varied with fixed step in the range required for the body to fall on Earth [FIG. 6 - a)].

Range for each throw angle is defined on the graph, i.e. intersection of the graph with X axis. The most efficient angle is defined by drawing these graphs for various throw angle.

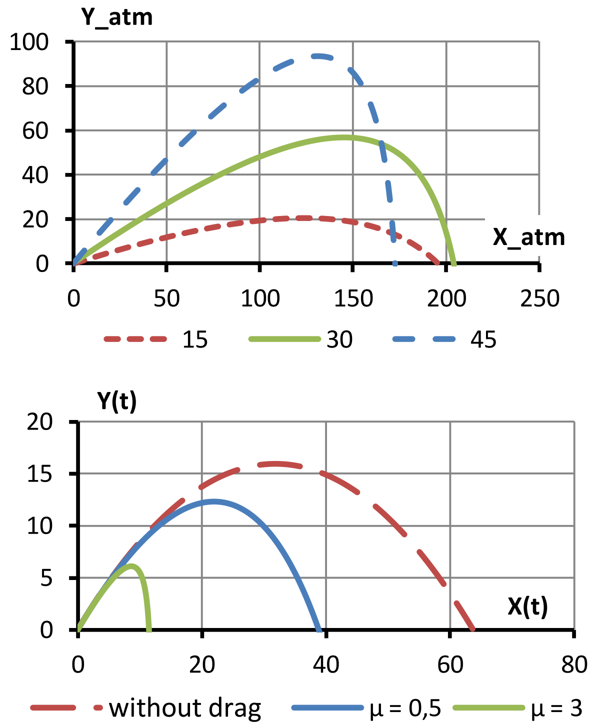

FIG. 6. Trajectories of thrown body depending upon: a) throw angle; b) aerodynamic drag coefficient

Each student studies trajectory of a body for an individual set of parameters (m, μ, V_0). At the end of laboratory activity each group of students (10-15 people) compare the results of their individual studies and make conclusions about the difference of trajectories with and without atmosphere [Fig. 6 - b)], about relationship between optimal throw angle and resulting trajectory from initial throw speed, and aerodynamic drag coefficient, and how to make a decision should you throw at low or high angle. Comparison of results is simplified by availability at Mission Control Centre of a multi-display board, where results from all computers may be shown simultaneously.

Laboratory Activity No 3 is related to receiving information from small satellite using backup downlink channel. Signal is received using Morse code, which is recorded into audio file, then represented graphically in a form of spectrogram, then is decoded. Activity also involves studying amplitude modulation of a signal [Fig. 7.]

Fig. 7: Receiving signal in Morse Code and familiarizing with basics of AM signal modulation.

When small satellites are out of range of main receiving station, they usually transmit data using SSB modulation, so signal is encoded in Morse Code (CW-signal). This type of data exchange is also used as backup communication channel, even though it can carry less data that FM signal, however it possesses several advantages, one of them is low power consumption.

Main computer uses TLE files to calculate satellite's coordinates, sends required targeting information (azimuth and elevation angles) to antenna controller and sends expected receiving frequency to transceiver, taking into account Doppler Effect. Radio signal received from satellite is then converted in transceiver into audio and is then sent to computer audio card where it can be recorded and processed. This signal is then transferred into text sequence of dots and dashes and then high-school students convert it to numbers and letters, which represent telemetry from the satellite. After that, telemetry decoder is used to receive hardware indications for this satellite for the concrete moment of time.

Laboratory Activity No 4 is related to mathematics and consists of representing a function as Taylor series. The goal of this activity is to strengthen the knowledge of differential calculation, which high-school students will come across at mathematical and engineering departments of various universities.

In mathematics it is sometimes possible to replace a function defining condition of a certain system by simplified formulae. This is reached by representing functions by Taylor series referencing basis point of the system x_0:

$$(x_0 + \Delta x) = \ (x_0) + \ '(x_0) \cdot \Delta x +$$
$$+\frac{1}{2!}\ ''(x_0) \cdot \Delta x^2 + \frac{1}{3!}\ '''(x_0) \cdot \Delta x^3 \ldots \qquad (2)$$

There are certain limitations for the usage of (2):

– Value of deviation (Δx) from basis point x_0 that still ensures the convergence of Taylors series;
– Number of terms in Taylor series to reach the required accuracy;
– Behavior of deviations of Taylor series from original function at different number of used terms and magnitude of such deviations.

As part of laboratory activity high-school students work with standard mathematical functions that are studied in high-school. They need to understand general approach to the usage of Taylor series when representing an elementary mathematical function in the vicinity of certain value of the variable. Microsoft Excel is used to create a model of Taylor series with consequently increasing number of used terms. Students use plots to show the dynamics of Taylor series relatively to the real value of the function in a specified point. Then stability of received Taylor series is studied by increasing the deviation (Δx) from initial value of the variable. Starting with certain value of such deviation Δx, Taylor Series diverge from original function with addition of more members, for example for equation $f(x) = \sqrt{x}$, [FIG. 8.].

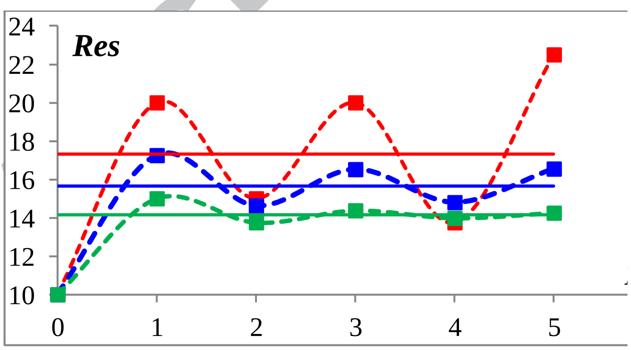

Fig. 8. Various cases of approximation by Taylor Series of function $y(x) = \sqrt{x}$ by using first 5 terms. Initial value of the variable is the same, while Δx is varied. Dashed lines connecting results of approximation are fictional and are shown just to add visibility to dynamics of researched process.

IV. EXAMPLES OF NEW EDUCATIONAL TOOLS FOR HIGH-SCHOOL STUDENTS (8-9 grades)

Space images of high and extremely-high resolution can be used to firm up knowledge of such subjects like geography or geometry. We will show examples of several practical geometrical tasks which can be offered to 8th or 9th grade high-school students. Imagery, required for these tasks, can be taken from mapping services - Google, Yandex and others. There are several examples of utilization of the resources of Youth Space Centre of Bauman University which we would like to describe below with respect to high-school students.

Example 1. Input data is a space image of Shukhov tower in Moscow (Fig. 9).

Fig. 9.Shukhov tower, Moscow

It is known that height of this tower is 148.3 meters. Another image shows main building of Moscow State University n/a Lomonosov [Fig.10]. Both structures are shown at the same space imagery. Knowing the height of Shukhov tower students are tasked to define:

- Height of Moscow State University building;
- Position of the center of the Shukhov tower.

Since both structures are at the same space imagery, the Sun is shining to both these structures at the same angle. Because of that tops of both structures, their bases and furthest points of their shadows form similar triangles [Fig.11]. Because triangles ABC and AB_1C_1 are similar, then ratios between the sides of these triangles can be shown as:

$$\frac{AB}{AB_1} = \frac{AC}{AC_1} = \frac{BC}{B_1C_1}$$

Length of BC side (height of Shukhov tower) is given, shadow lengths AC (from tower) and AC_1 (from University top mast) can be measured with a ruler.

Then, height of the University (to the top of the mast) can be defined using this ratio:

$$B_1C_1 = \frac{BC \cdot AC_1}{AC}$$

Fig. 10.Main building of Moscow State University

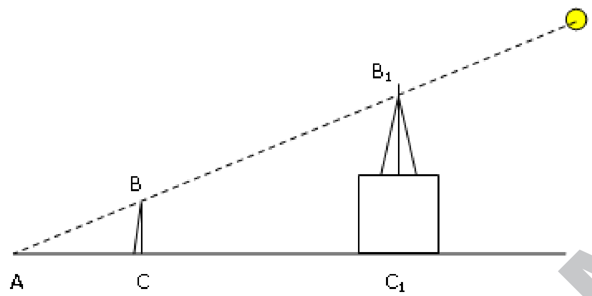

Fig. 11.Similar triangles, formed by direction of solar rays

In order to define the diameter of the bottom of circular foundation of the Shukhov tower it is first needed to define the center of the foundation. At first it is required to pick any three points on the circular shape of the foundation and to connect these with lines as shown at Fig. 9 (yellow dotted line), then draw central perpendicular to each of these lines (blue lines). Intersection of these perpendiculars – based on the theorem about diameter perpendicular to a chord – will be the center of the foundation.

An important part of the work is the comparison of received results with actual values calculation of relative and absolute errors. It is also useful to discuss the possible reason of such errors, the main of which is accuracy of the measurement and direction of the image. It is clearly seen at Fig.10 that images are not taken exactly perpendicular to the surface of the Earth, but at oblique angle. While this will not impact the accuracy of defining the center of foundation of the tower, it will however cause an error when defining the height of the university building.

Example2.Space image shows a pond in Lefortovo Park, opposite to main building of Bauman University in Moscow [Fig.12]. Diameter of foundation of Shukhov tower (from previous example) is known. It is required to define the area of the pond.

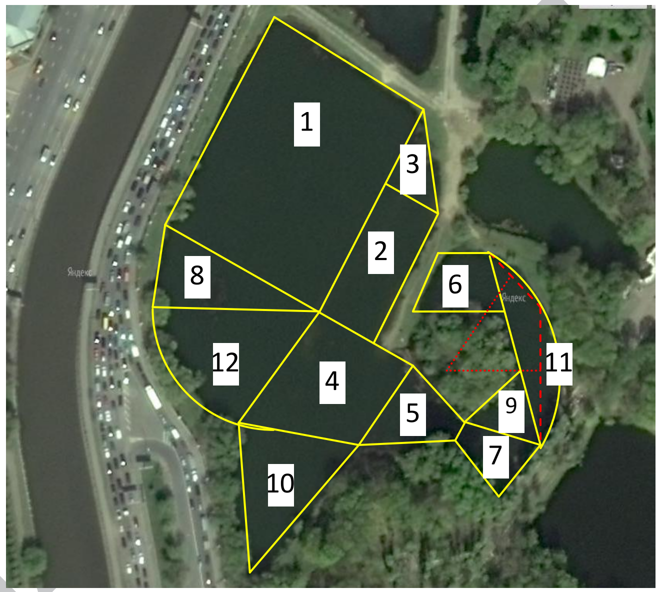

Fig.12.Pond in Lefortovo Park.

Using known length of diameter (and radius) of foundation of Shukhov tower it is possible to define scale of the image, i.e. to understand how many meter on the Earth surface correspond to 1mm (smallest scale of school rulers) on the image.

In order to define area of the pond, which is of irregular shape, it is needed to split the shape of the pond into standard shapes which areas can be defined by using standard geometry formulae. When using such approach the result will of course differ from real value (especially since there is a build-in error related to non-perpendicular direction at which this image is taken), however some errors could cancel each other out. One of possible option of such split is shown at Fig. 8 (yellow lines). Shapes 1 through 4 contain right angles, shapes 5 through 7 are trapezoids, shapes 8 through 10 are triangles. Shape 11 is a piece of a circle (red lines are showing the search for the center of such circle), while shape 12 is a sector of a circle.

As seen at Fig. 12 almost all standard shapes in the geometry course are covered when the shape of the pond is split into shapes. It is assumed that in order to define the area of shapes 1 through 12 the only measurement devices required are a ruler and a protractor.

V. FEEDBACK FROM THE TARGET AUDIENCE

In the year 2016 ninety eight laboratory courses were developed at Bauman University within the initiative aimed at increasing quality of acquisition of science knowledge by high-school students. Such courses were developed in the fields of physics (thermodynamics, molecular-kinetic theory, electrodynamics, optics and mechanics), information technologies and mathematics. These laboratory courses were implemented in a form of 214 classes within 98 courses which were attended by 2403 high school students in Moscow. After completion of each course 1770 anonymous surveys were collected in order to define deficiencies of the format and content of these courses. Each group of students was accompanied by teachers (total of 204 teachers), who also participated in the survey (138 feedbacks were collected).

Results of the surveys are shown in Fig. 13 in a form of three diagrams, showing scores in 1-to-5 range, using three parameters: General Impression, Level of Presenting and Practical Value. Left value in each grouping is an average mark given by teachers, right value is an average mark from students, and central value is an overall average from all participants. The value of standard deviation should be considered as 0.2-0.3 based on our experience.

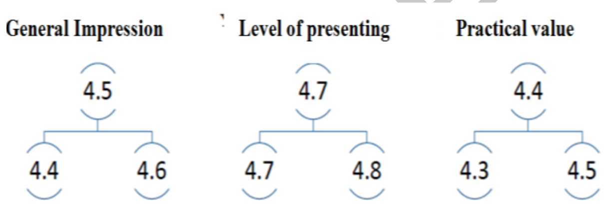

Fig. 13. Results and Evaluation of new Program

These diagram shows that both teachers and students assigned high marks to the courses, that confirms the importance of conducting laboratory courses for high-school students at universities while utilizing most modern equipment and technologies.

VI. CONCLUSIONS

Evidently, current decrease of interest in scientific disciplines among high-school students handicaps their preparedness to become technically competent professionals in the future.

In order to raise knowledge and creative skills among high-school students at a substantially higher level it is important to strengthen inter-disciplinary connections, which in turn requires to integrate scientific knowledge and theoretical research with practical activities of high school students.

Centers of Collective Use, Scientific Educational Centers (SEC) and Departmental Laboratories of technical universities should become basic components of infrastructure, aimed at ensuring scientific and research activity of high-school students.

Access for high school students to scientific-research work at SECs, and access to modern equipment and innovative programs significantly increases their interest towards studying physics, mathematics, information science and other science disciplines.

The process of uniting in one educational environment all components of this sequence: High-School – COC/SEC/DL – Information Resources – Knowledge – Industrial Base allows to develop and implement into educational process of new educational tools, for example laboratory activities with demonstration of physical phenomena at SEC's.

In general such a comprehensive approach to implement profiled education with the use of the project method, based on strengthening inter-disciplinary connections by the use of new educational tools, is aimed to increase the interest of students towards engineering and technical disciplines and to motivate senior high-school students to continue education in scientific and technological majors. The inter-disciplinary connections between SEC's and schools permit:

- to extend and to firm-up the basic knowledge in physics, math and computer;
- to show how the obtained knowledge works in practice;
- to give experience in carrying out of physical and technological experiments;
- to make scientific and technological knowledge popular;
- to prepare high-school students for studying at technical universities.

To advance development of new educational tools we suggest creating special education means for school teachers. That will ensure their awareness about existing laboratory practices and give teachers confidence to present laboratory courses and answer questions.

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