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Investigation of Wireless Sensor Deployment Schemes for In-Situ Measurement of Water Ice near Lunar South Pole

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Abstract: It has been known for many years that the Moon has no atmosphere and hence no stable surface water. Cold traps on the Moon near lunar South Pole are understood to have water ice present in them due to striking of comets and meteorites with the Moon. Observations from very recent lunar missions indicate presence of water on the Moon. However, all such methods are based on remote techniques and no in-situ measurements have been done so far. In order to carry out in situ measurement of water ice and also to study properties of Regolith near lunar South Pole, it is planned to deploy wireless sensor network on lunar surface. Deployment of sensors on a planet or outer body like the Moon is really a challenging task and needs theoretical understanding before implementing through any space mission, as it involves huge amount of investment. In this article, we have attempted to understand theoretical aspects involved in deployment of sensors on the Moon. Minimum number of sensors needed in each topology to cover a given sensing region has been found assuring wireless connectivity. Derived equations governing trajectory of deployment topologies have been executed using code in MATLAB and deployment costs for all three schemes are compared. *Copyright © 2009 IFSA.*

Keywords: Wireless sensor network, Deployment strategy, Coverage, Wireless connectivity

1. Motivation and Introduction

It is known that the Moon has no atmosphere and hence no stable surface water. However, few molecules of water might have been present due to striking of water bearing comets and meteorites with the Moon and over thousands of years, these molecules might have been transferred to polar

region where they could be trapped inside cold traps due to very low temperature of permanently shadowed region. It is understood that water ice may be present in permanently dark regions inside craters near lunar South Pole. Volatiles like water and CO_2 can provide information about history of the Moon, cometary impact and stratigraphic record. Also, presence of volatiles provide source of rocket fuel and water, CO_2 & nitrogen from ammonia form essential elements for life.

There has been contradiction between orbiter Clementine mission data and Earth based Arecibo Radar Observatory data regarding the presence of water ice at lunar South Pole [1]. Observations from very recent lunar missions, for example as given by Pieters C. M. et al [2] indicate presence of water on the Moon. However, all such methods are based on remote techniques and no in-situ measurements have been done so far near the lunar South Pole. In order to carry out in situ measurement of water ice and also to study properties of Regolith near lunar South Pole, it is planned to deploy Wireless Sensor Network (WSN) on lunar surface by future lunar mission.

For any WSN, it is utmost important to deploy sensors with optimum choice. In case of manual deployment, sensors can be deployed at the site of interest with accurate positioning. This type of deployment and partly controlled deployment, in which moving vehicle can drop sensors from predefined points and sensors reach to the land and settle there, are used for terrestrial sensor networks normally. However, in hostile environment like that on the Moon, manual deployment or partly controlled deployment is not feasible as it is outside the Earth and therefore, only random deployment is the choice left, which may be achieved by means of probably a lander type packet, falling from the orbiter or a shooter mounted on the rover. This has motivated us to study few deployment strategies for deployment of sensors on the Moon and understand various deployment parameters as well as minimum number of sensors needed to cover a probing region of interest near lunar South Pole.

Various deployment techniques have been reported in the literature like random deployment or a planned grid deployment given by Leoncini, M. et al and Chakrabarty, K. et al [3, 4, 5]. However, these are mostly for terrestrial applications, adopting grid strategy with square cells for environmental monitoring in areas, which are not easily accessible or reachable. Sensors are deployed through airplane moving above these regions and uncertainty involved is addressed by Y. Zou and K. Chakrabarty [6]. For applications on the Earth, aircraft can fly horizontally and square regions can be covered. However, for the target application on the Moon, deployment of sensors by means of many sensor packets, falling from the orbiter, cannot be done in horizontal direction economically as there remains limit of size and weight for space missions. A. Howard et al [7] uses self-deployment scheme and A. Howard et al [8] uses potential field based sensor deployment, which cannot be implemented on the Moon easily. S. Kumar et al [9] shows barrier coverage with sensors and uses random deployment also. Y. Zou and K. Chakrabarty [10] use random deployment initially and apply algorithm to maximize sensor field coverage. Jiming Chen et al [11] give survey on sensor deployment algorithms. G. L. Wang et al [12] discusses movement assisted sensor deployment. X. Q. Wang et al [13] gives a virtual rhomb grid-based movement-assisted sensor deployment algorithm, which integrates both deterministic and self-organizing deployment in a unified framework. P. Wan and C. Yi [14] discuss sensor deployment as Poisson or uniform point process in square or disk region. X. Bai et al [15] suggest optimal deployment pattern. P. N. Balister and S. Kumar [16] compare a random versus deterministic deployment of sensors in a presence of failure and placement error. For lunar or planetary application, random deployment like that given by Morteza Maleki [17] and T. Clouqueur et al [18] is to be adhered to by throwing sensors in someway in the sensing zone. Moreover, sensors are to be deployed on the lunar surface having limited line-of-sight communication range, typically 200 m for sensor in design. All such sensors cannot communicate to the orbiter but transmit their information to nearest neighbor and ultimately information flows to the cluster head. This cluster head is supposed to have higher capacity and can transmit signal to the orbiter, being on the rover. It is, therefore, important to address the issue of wireless connectivity for sensor nodes, as it would decide minimum distance to be kept between them to complete the network and to remain in line-of-sight

communication range. Communication on the Moon is expected to be better than that on the Earth due to vacuum on the Moon.

In circular and spherical segment schemes suggested in this article, it is assumed that sensor packets (having some initial rotation to maintain the direction) are detached from the orbiter or satellite orbiting around the Moon and fall vertically downward towards the selected crater of the Moon. It is further assumed that packet velocities are damped when they reach near the lunar surface and sensors are ejected from the packet at a certain height from the surface. Such assumptions are not discussed here, because these are taken care by satellite integration team. Third deployment scheme, i.e., parabolic scheme is also discussed in this article which can launch tiny wireless sensors inside the crater using a mini launcher (on lander or rover at the crater edge). For all there methods, it is assumed that required tiny wireless sensors are available which can work in lunar environment. The discussion on hardware design of such sensors is beyond the scope of this article and therefore not reported here. The hardware design of such wireless sensors is underway for future wireless sensor network on the Moon. Once the sensors become ready, they can be put in appropriate scenarios to check practical aspects of such deployment schemes. Newton's laws of motions remain valid for planetary applications and have been used for deriving equations governing trajectories of various topologies. Rest of the paper is organized in following way: section 2 describes circular deployment strategy with related simulation results, section 3 describes spherical segment scheme along with results, section 4 suggests parabolic launching deployment by shooter and the article ends with discussion and summary.

2. Circular Deployment Strategy

Considering target application for future planetary exploration, only limited amount of size and weight are permitted for payloads/sensors due to many limitations like launching facility, energy and cost involved. If one can reduce number of sensors to be deployed, it can further reduce weight and size, but at the cost of reduced topographical coverage. However, number of sensors is also decided by line-of-sight communication range between sensors. We assume an application scenario in which sensors are ejected from an orbiter in a circular graphical region (with radius R) to be studied, in a two dimensional plane.

As mentioned above, it is assumed that enough number of water ice sensors capable of working in hostile environment are available, sensor packet is detached from the orbiter, its initial velocity is reduced and after reaching a particular drop point with height 'h' from the lunar surface, sensor packet is opened by releasing pressure inside. Small sensors are packed between two circular rings as shown in Fig. 1, with a facility to release pressure from centre of inner ring.

Fig. 1. Circular ring package for sensor deployment.

After achieving desired altitude, the sensor packet is opened with horizontal thrust to throw sensors in radial directions, creating some initial horizontal separation among them. This initial horizontal separation among sensors is needed for geographical coverage of crater, as there is no wind on the Moon and hence no natural horizontal force exists. Also, from this initial height 'h', all sensors start their downward journey towards the lunar surface due to gravity of the Moon. Drop point (from where package is opened) and its corresponding point on lunar surface is assumed to be origin (actually centre of the ring package), i.e., at (0, 0) for simplicity for respective planes. If sensors are packed between two circular rings having initial locations as (r, θ_j), where $j = 1,2,...,n$ and r is average of two radii of circular rings of sensor packet, then angular separation between any two consecutive sensors is approximately $\frac{2\pi}{n}$ for n sensors. Arbitrarily,

For vertical velocity components,

$$-h = v_i t + \tfrac{1}{2} a t^2 = -\tfrac{1}{2} \cdot (1.622) t^2 = -0.811 t^2$$

giving time of flight,

$$t = (1.11) \cdot h^{0.5} \tag{1}$$

Also,

$$-v_{fy} = v_{iy} + at = -(1.622)t = -1.8h^{0.5}$$
$$\therefore v_{fy} = 1.8h^{0.5}$$

For horizontal velocity components, distance travelled by each sensor is,

$$d = v_i t + \tfrac{1}{2} a t^2 = v_{ix} t = (1.11) \cdot v_i h^{0.5} \tag{2}$$

Also, $v_{ix} = v_{fx} = v_i$ and $v_{iy} = (1.8)h^{0.5}$ giving final impact velocity of sensor as

$$v_f = (v_i^{\,2} + 3.24h)^{0.5} \tag{3}$$

If pressure p is released from the centre of inner ring and vertical dimension of ring structure is y, then force exerted on inner ring due to this pressure is $(2\pi r_i yp)$ and distance travelled by each sensor will be d from its initial rest position, where r_i is radius of inner ring. Under this scenario, energy used for horizontal thrust is $E = 2\pi r_i ypd$, and each sensor would have $E/(\kappa \cdot n)$ as initial energy, which will be converted into initial kinetic energy giving initial horizontal velocity $v_{ix} = v_i$. Here, κ is packet filling factor, defined as a ratio of number of sensors required to fully fill the packet to the number of sensors actually filled in the packet.

$$\frac{E}{\kappa \cdot n} = p \cdot (2\pi r_i y) \cdot d = p \cdot (2\pi r_i y) \cdot v_i t = \tfrac{1}{2} m_s v_i^{\,2},$$

where m_s is mass of each sensor.

$$p = \frac{m_s d}{4.9284 \pi r_i yh} \tag{4}$$

Also,

$$v_i = \frac{4\pi r_i ypt}{m_s}$$

and $v_i \propto p$, as expected.

Positions of all sensors would be on a circular path (assuming crater surface as flat for simplification, initially) with radius as $R = r + d(\approx d)$ and positions on the surface are given by (R, θ_j), where $j = 1,2,...,n$. Final radius R depends on travelled distance d, which in turn depends on initial horizontal velocity v_{ih}. This initial velocity is created due to applied blast energy. Higher the blast energy, more is R and more is n for a given line-of-sight communication distance between sensors (d_s). Since, some minimum energy $(E_{\min})$ is needed to blast the packet for achieving required coverage of sensing region with radius R and for a given probing region of radius R, some minimum number of sensors is required to assure line-of-sight wireless communication distance, this gives lower bound on number of sensors to be deployed. Upper bound on number of sensors is given by maximum permissible mass in payload and maximum energy $(E_{\max})$ is needed for creating the blast. In above calculations, altitude of deployment or drop point h is known in advance, hence time of flight can be found. In present application scenario, probing region of interest is about 1 km in diameter near the lunar South Pole and it is actually decided based on real potential site conditions. Some of the regions near lunar South Pole do not receive sunlight and are very cold. Such regions are called permanently dark regions and there is a possibility of water ice mixed with lunar Regolith in such regions. Deploying sensors in larger area can provide information of Regolith properties in larger geographical area. Diameter of probing region depends on such site selection and may be planned to be about 1 km. Larger area coverage is always desirable for finding potential site having water, but it requires more number of sensors, which in turn put requirement of larger size and weight of payload, a constraint for a mission. Hence for studying parameters, a circular region with radius R of 0.5 km is considered here, which may be achieved by few target sensors with communication range of 200 m. However, it is easy to obtain parameters for other values as well. All remaining parameters related to topology can be obtained. Fig. 2 (a) shows plot of sensor fall time versus altitude of deployment point and it is useful in calculating starting time of network. Fig. 2 (b) shows initial velocity required by sensors for given deployment height and radius (or distance travelled) of sensing region. This parameter is useful in estimating required deployment energy to eject sensors from particular altitude. Fig. 2 (c) shows impact velocity of sensors at the time of reaching lunar surface, for given altitude and initial velocity. It is necessary to know impact velocity for designing shielding of sensor node and it should be within withstanding limit of material used for shielding, so that sensor node does not break due to impact on lunar surface. For typical sensor under design having estimated weight of 200 gm, radius of deployment ring as 1 m with thickness as 3 cm, packet filling factor of 3 and sensors (under design) having estimated communication range as 200 m; deployment pressure can be obtained from Fig. 2 (d) and deployment energy can be obtained from Fig. 2 (e), respectively. Equation (6) for number of sensors, which is derived in the following part, is used in computing the energy shown in Fig. 2 (e).

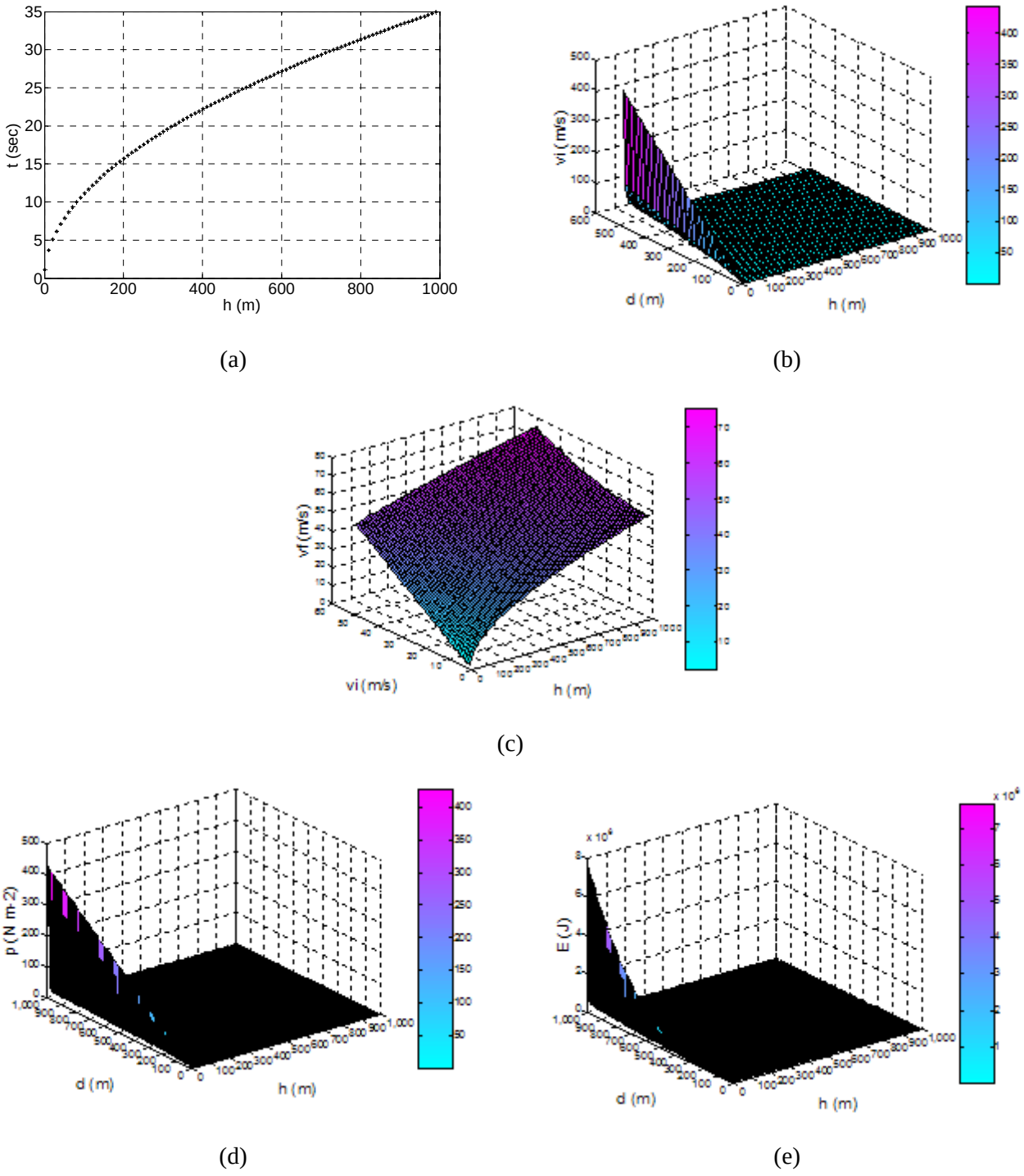


Fig. 2. (a) Sensor fall time vs. altitude, (b) Initial velocity vs. altitude & distance to be covered, (c) Impact velocity vs. altitude &initial thrust velocity, (d) Deployment pressure vs. altitude & distance to be covered and (e) Deployment energy vs. altitude & distance to be covered.

Fig. 3 (a) depicts geometry for obtaining minimum number of sensors, Fig. 3 (b) shows practical positions of sensors and Fig. 3 (c) shows minimum number of sensors required for a given sensing region and for a given line-of-sight communication range of sensors. As shown in Fig. 3 (a), for n sensors on a circle of radius R with angle between any two consecutive sensors as θ, Cosine law can be applied in a triangle having two sides as radii of circle (R) and the third side as line-of-site communication distance (d_s) between two sensors under consideration.

$$Cos\theta = \frac{R^2 + R^2 - d_s{}^2}{2 \cdot R \cdot R} \tag{5}$$

Simplifying above equation by taking angular separation between two sensors as $\theta = \frac{2\pi}{n}$, following equation can be obtained for number of sensors required to probe a particular region of interest.

$$n = \frac{2\pi}{Cos^{-1}(1 - \frac{d_s{}^2}{2R^2})} \tag{6}$$

Positions of sensors after deployment will be

$$(R, \theta_j) = (R, \frac{j2\pi}{n}) = (R, jCos^{-1}(1 - \frac{d_s{}^2}{2R^2})),$$

where $j = 1,2,...,n$ and deployment energy required for initial thrust is

$$E = \kappa \cdot n \cdot \tfrac{1}{2} m_s v_{ix}{}^2 = \kappa \cdot \frac{2\pi}{Cos^{-1}(1 - \frac{d_s{}^2}{2R^2})} \cdot \tfrac{1}{2} \cdot m_s v_{ix}{}^2$$

$$\therefore E = \frac{\pi \cdot \kappa \cdot m_s \cdot d^2}{1.2321h \cdot Cos^{-1}(1 - \frac{d_s{}^2}{2R^2})} \tag{7}$$

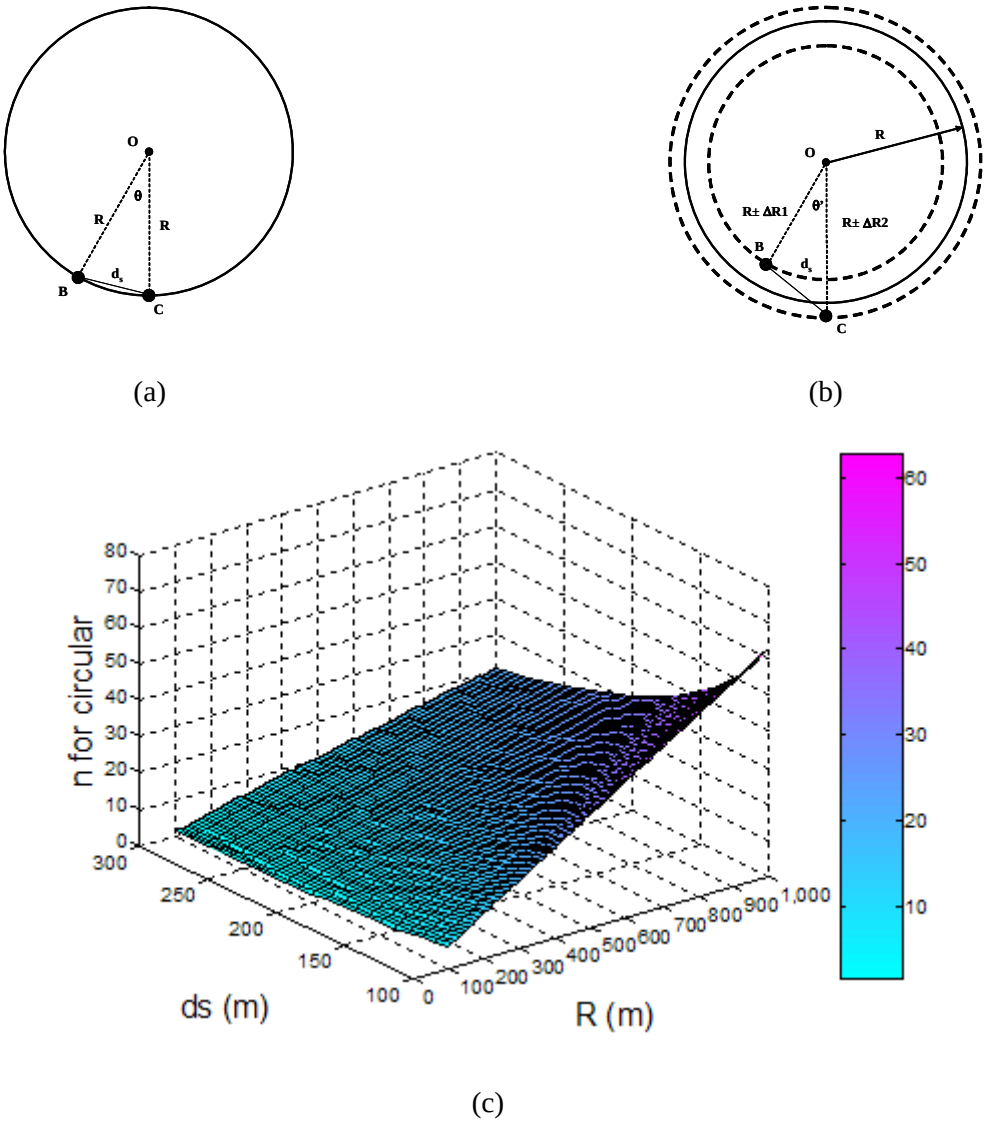
Due to uneven surface topology inside a selected crater or on selected site, sensors may slide or roll over curved paths and reach final settled positions (R', θ_j'). These final positions of sensors, if calculated using location information, can provide information of local curvature of crater, if not exactly then approximately and may also help in adding further details in terrain mapping of crater.

Considering example for probing a typical circular region with (arbitrarily chosen) radii of 251 m and 500 m, using a circular sensor packet of vertical dimension 3 cm and inner radius 1 m, filled with sensors of 200 grams each and ejected from an altitude of 500 m, various parameters are found and are summarized in Table 1.

Table 1. Typical deployment parameters for circular scheme.

Parameter	Value for R = 251 m	Value for R = 500 m
Sensor Fall Time	24.82 sec	24.82 sec
Initial Velocity	10.07 m/sec	20.1 m/sec
Impact Velocity	41.49 m/sec	44.99 m/sec
Number of Sensors	7.67 (8*)	15.6 (16*)
Total Pressure	4.95 (5.17*) N/m^2	20.11 (20.62*) N/m^2
Total Blast Energy	233.23 (243.37*) J	1890.77 (1939.25*) J

*For nearest integer no. of sensors



(a) (b)

(c)

Fig. 3. (a) Geometry for minimum number of sensors in circular topology, (b) geometry for practical sensor positions and (c) Minimum number of sensors required for circular topology vs. radius of sensing zone (R) and line-of-sight communication range (d_s).

In case of circular type deployment, sensors are supposed to fall on circular region. However, this cannot always be the case due to uneven surface topology on the Moon. This can cause the sensors to either roll or slip when they reach the lunar surface and settle to slightly different positions. In effect, they make different topology instead of a perfect circle. However, wireless connectivity must be achieved under this practical scenario in order to complete the network. Suppose two adjacent sensors fall at positions of circles with radii $R \pm \Delta R1$ and $R \pm \Delta R2$ respectively, where $\Delta R1$ and $\Delta R2$ are changes in radii for actual positions as depicted in Fig. 3 (b). These adjacent sensors make an angle of θ' and they must have distance d_s between them to complete the network. In case, if they fall at larger distances than d_s, they can't establish communication. If new angle θ' is less than old angle θ, it guarantees wireless connectivity. Under this practical scenario, condition on permissible change in radius for two adjacent sensors, $\Delta R1$ and $\Delta R2$ are obtained as below.

$$\theta' \le \theta$$

$$\therefore Cos\theta' \ge Cos\theta$$

$$\therefore \frac{(R \pm \Delta R1)^2 + (R \pm \Delta R2)^2 - d_s{}^2}{2 \cdot (R \pm \Delta R1) \cdot (R \pm \Delta R2)} \ge \frac{R^2 + R^2 - d_s{}^2}{2 \cdot R \cdot R}$$

Simplifying above inequality, we can obtain following condition for wireless connectivity in case of practical positions as

$$\frac{-R \cdot (\sqrt{\frac{\Delta R1}{\Delta R2}} \mp \sqrt{\frac{\Delta R2}{\Delta R1}})^2}{(\pm \frac{1}{\Delta R} \pm \frac{1}{\Delta R1} \pm \frac{1}{\Delta R2})} \le d_s{}^2 \tag{8}$$

The change in radius $\Delta R1$ and $\Delta R2$ for any two neighboring sensors can be either positive or negative and only magnitude should be taken in Equation (8).

Once sensors have been deployed in circular zone, rover can move near to deployment area and complete wireless link to orbiter or satellite.

3. Spherical Segment Deployment Scheme

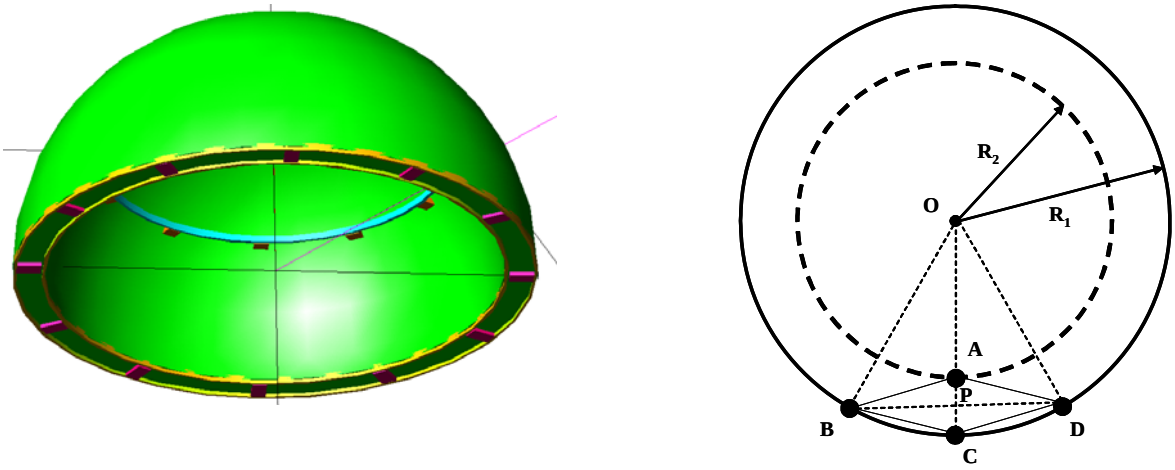
Target sensing region is taken here again as a circular region (typically 1 km in diameter, as explained earlier) and sensors are now to be dropped on two circular paths with radii of R_1 and R_2 with $R_1 > R_2$. To achieve wireless connectivity and degree of coverage under this scenario, sensors are packed in circular ring structure as in case of circular strategy described, but now, there are two similar ring structures stacked in vertical direction so as to make an overall spherical segment structure, as shown in Fig. 4 (a). For obtaining mounting angle of upper (second) ring structure from that of first in a vertical stack inside spherical packet, geometry shown in Fig. 4 (b) is used. For example, three sensors are to be deployed at positions B, C and D on outer circular path having BC = CD = d_s, as line-of-sight wireless communication range. The forth sensor position A is to be on inner path such that rectangle ABCD is a rhombus; this is because sensor at A should also be able to communicate to sensors at B or D, once the network is established. After using this topology, the ratio of two radii, i.e., $\frac{R_2}{R_1}$ can be found from the geometry and given below:

$$\frac{R_2}{R_1} = 1 - \frac{d_s{}^2}{R_1{}^2} \tag{9}$$

Typically, for outer circle with 500 m radius in considered example, the inner circle would have radius of 420 m and ratio of two radii would be 0.84. If first ring structure for outer circle is kept at 0 degree in the hemisphere, then the other ring structure is to be kept at 32.86 degree from the first on the hemispherical segment. In general, hemispherical structure can be designed based on real application using derived equation.

Now, consider that this hemispherical packet, having radius r and vertical dimension of each ring y (as it was taken for circular), is to be released from the satellite similar to the circular case. All sensors are assumed to be placed in radial directions inside the individual ring structure of hemispherical

packet. Sensor packet is detached from the orbiter and its initial velocity is damped; when it attains a desired altitude from surface. Radial lines drawn from centre of the sphere to mid points of the vertical dimension of ring structure are indicative of directions of force exerted due to pressure (p), which is released from the centre after achieving desired altitude.



(a) (b)

Fig. 4. Position of sensors in (a) sensing region and (b) spherical deployment package.

Force on first ring is $(2\pi \cdot r \cdot y \cdot p)$ Newton and sensors in this ring would travel total horizontal distance d; due to this exerted force. However, force on the second ring would now be $(2\pi \cdot r \cdot y \cdot p \cdot Cos\theta)$ Newton in horizontal direction and $(2\pi \cdot r \cdot y \cdot p \cdot Sin\theta)$ Newton in vertical direction, due to splitting of velocity vector in two dimensions. This would cause sensors in second ring to travel a distance 0.84 times less than those for the first ring for present case. This becomes a special case of a parabolic strategy (described in next section), in which initial velocity is taken equal for all sensors and launching angles can vary during deployment; except the condition that, here a group of sensors stacked in vertical direction are deployed together at a particular angle; while in case of parabolic strategy, only single sensor is deployed at a particular angle. Equations governing this deployment scheme are given below (and merge with circular scheme for first ring structure, having 0 degree as position angle of ring in the hemisphere, as expected). The plots are similar to those given in next section for the case, when launching angles are varied and therefore plots are not given here.

Time of flight of sensor,

$$t_j = 0.617(v_i Sin\theta_j - v_f Sin\phi_j)$$

Distance travelled by sensor,

$$d_j = 0.617 v_i Cos\theta_j \cdot (v_i Sin\theta_j - v_f Sin\phi_j)$$

Depth of final sensor position from drop point,

$$h = 0.308 \cdot \{(v_i Sin\theta_j)^2 - (v_f Sin\phi_j)^2\}$$

Impact angle of sensor with horizontal,

$$\phi = -Tan^{-1}\{(Tan^2\theta_j - \alpha \cdot Sec^2\theta_j)^{0.5}\}$$

Factor governing impact angle,

$$\alpha = \frac{3.244h}{v_i^{\ 2}}, \tag{10}$$

where j = 1 and 2.

Trajectory parameters and deployment energy for individual ring can be obtained using method given for circular by splitting vector in two directions. Also, stacking of deployment rings in spherical segment can be done in reverse way, i.e., smaller ring can be mounted in lower hemispherical part of packet instead of mounting on upper part, slightly modifying parameters.

Number of sensors for such type of deployment can be given by Equation (6) but now for individual ring. Minimum number of sensors in this scheme is given by addition of number of sensors in both rings.

$$n = \frac{2\pi}{Cos^{-1}(1-\frac{d_s^{\ 2}}{2R_1^{\ 2}})} + \frac{2\pi}{Cos^{-1}(1-\frac{d_s^{\ 2}}{2R_2^{\ 2}})} \tag{11}$$

However, $\frac{R_2}{R_1} = 1 - \frac{d_s^{\ 2}}{R_1^{\ 2}}$ and therefore, $R_2 = R_1 - \frac{d_s^{\ 2}}{R_1}$. Substituting this value of R_2 in Equation (11), one can obtain following equation for minimum number of sensors required for this scheme.

$$n = \frac{2\pi}{Cos^{-1}(1-\frac{d_s^{\ 2}}{2R_1^{\ 2}})} + \frac{2\pi}{Cos^{-1}(1-\frac{d_s^{\ 2}R_1^{\ 2}}{2(R_1^{\ 2}-d_s^{\ 2})^2})} \tag{12}$$

Number of sensors in first and second ring are given by first and second terms of Equation (12) or by Equation (6) as 16 and 14 respectively, with R = R_1 = 500 m and R = R_2 = 420 m. for probing two circular zones with assured wireless connectivity. Fig. 5 shows plot of minimum number of sensors in spherical segment type strategy versus sensing zone radius & line-of-sight communication range. Once sensors are deployed on surface, rover can move near to deployed sensors and complete the network.

Analysis of radius sensitivity for this type is on similar ground as that for circular topology. If radius of outer circle is taken as $R1$, actual position of first sensor is $R1+\Delta R1$ and actual position of second sensor is $R1+\Delta R2$ then Equation (8) is valid condition for establishing communication between any two adjacent sensors on outer ring with R replaced by $R1$, where $\Delta R1$ and $\Delta R2$ represent change in radius with respect to $R1$, due to actually occupied positions.

If third senor (supposed to be on inner circle with radius $R2$) has actual position as $R2+\Delta R3$ (where $\Delta R3$ is change in original radius $R2$), then it can always be referenced with respect to the radius of outer circle $R1$. Thus, $R2+\Delta R3$ position may be considered as $R1+\Delta R3'$ (where $\Delta R3'$ is change in radius with respect to $R1$) and now again Equation (8) can be applied to obtain condition for wireless connectivity. Therefore, derivation of sensitivity analysis is not repeated here.

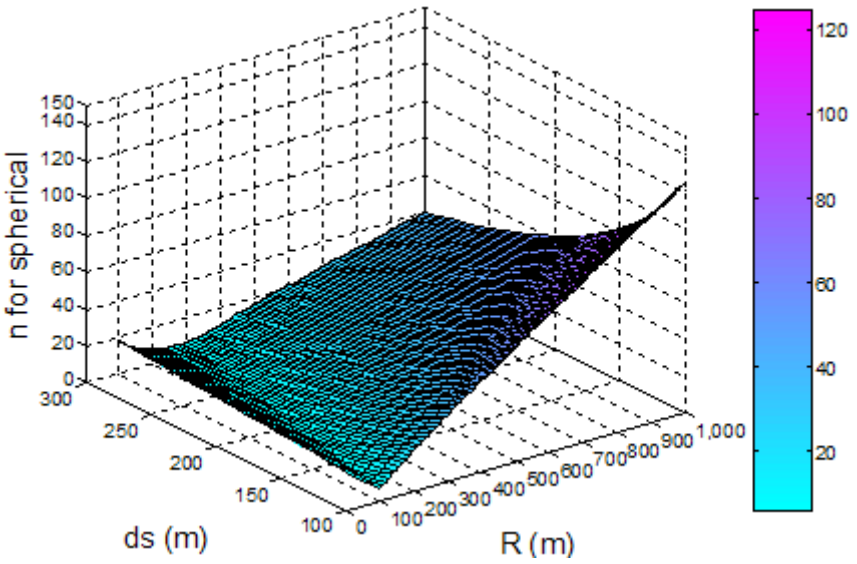


Fig. 5. Minimum number of sensors in spherical scheme vs. radius of sensing zone (R) & line-of-sight communication range (d_s).

4. Parabolic Launching Strategy

Under this deployment scheme, lander needs to carry a mini launcher (or shooter) which can either be mounted on a rover or on lander. Discussion of mini launcher is beyond the scope of this work and not mentioned here. After landing on lunar surface, rover should reach near the edge of a selected crater. Being at the edge of a crater, it should launch sensors at different positions inside the crater by selecting various vertical launching angles with respect to horizontal axis and also by varying initial velocities of sensors. The shooter can also have capability to vary angles in horizontal plane as well, to cover required probing region of interest in lateral direction. However, angle in horizontal plane does not affect trajectory path (since the crater diameter is very large as compared to sensing region) and may be avoided in calculations. Under this scenario, choice remains as (1) when each sensor is deployed with the same initial velocity but with varying vertical launching angles and (2) when each sensor is launched with the same vertical launching angle but with varying launching velocities. The geometry of the scheme is shown in Fig. 6 (a), topology for number and positions of sensors are depicted in Fig. 6 (b) and pictorial view at crater site is shown in Fig. 6 (c).

Assuming mass of each sensor as m_s and its initial launching velocity v_s, momentum imparted by launcher is $m_s v_s$ and energy needed is $\frac{1}{2} m_s v_s^2$. If there are n sensors, total initial kinetic energies for two cases respectively are

$$E_1 = \sum_{i=1}^{n} \tfrac{1}{2} \cdot m_{si} \cdot v_{si}^{\,2} = \tfrac{1}{2} \cdot n \cdot m_s \cdot v_s^{\,2} \tag{13-a}$$

$$E_2 = \sum_{i=1}^{n} \tfrac{1}{2} \cdot m_{si} \cdot v_{si}^{\,2} = \tfrac{1}{2} \cdot m_s \cdot \sum_{i=1}^{n} v_{si}^{\,2} \tag{13-b}$$

Since, sensors are to be deployed at different locations (for example, in a straight line for a particular setting of angle in horizontal plane), launcher being at the edge of a crater would shoot each sensor with either different velocities or with different angles (effectively making horizontal components of velocities different). In case of equal velocity launching scheme, total energy is n times the energy

required for a single sensor and some energy is also consumed in changing the launch angle. However, in case of varying velocities case (with the same angle), total energy required is to be less than that in the first case (with velocity equal to the highest velocity in the second case). However, exact comparison is dependent on the choice of parameters for a particular type of scheme.

For deploying n sensors, each having transmission range of d_s meters (typically 200 m) and assuming one sensor/relay is present at the edge of crater with the same transmission range d_s, the positions of sensors and launching angles can be found. Initial velocities are $v_1, v_2, ..., v_n$ and launching angles are $\theta_1, \theta_2, ..., \theta_n$. By using equations of motion and concept of parabolic trajectory, following equations are obtained, where $j = 1,2,...,n$. Distances of individual sensors from origin (launching place) are $d_1, d_2, ..., d_n$.

Time of flight of sensor,

$$t_j = 0.617(v_i Sin\theta_j - v_f Sin\phi_j)$$

Distance travelled by sensor,

$$d_j = 0.617 v_i Cos\theta_j \cdot (v_i Sin\theta_j - v_f Sin\phi_j)$$

Depth of crater where a sensor is deployed from shooter,

$$h = 0.308 \cdot \{(v_i Sin\theta_j)^2 - (v_f Sin\phi_j)^2\}$$

Impact angle of sensor with horizontal,

$$\phi = -Tan^{-1}\{(Tan^2\theta_j - \alpha \cdot Sec^2\theta_j)^{0.5}\}$$

Factor governing impact angle,

$$\alpha = \frac{3.244h}{v_i^{\ 2}} \tag{14}$$

for a case when velocities are same.

Time of flight of sensor,

$$t_j = 0.617(v_{ij} Sin\theta - v_{fj} Sin\phi)$$

Distance travelled by sensor,

$$d_j = 0.617 v_{ij} Cos\theta \cdot (v_{ij} Sin\theta - v_{fj} Sin\phi)$$

Depth of crater where a sensor is deployed from shooter,

$$h = 0.308 \cdot \{(v_{ij} Sin\theta)^2 - (v_{fj} Sin\phi)^2\}$$

Impact angle of sensor with horizontal,

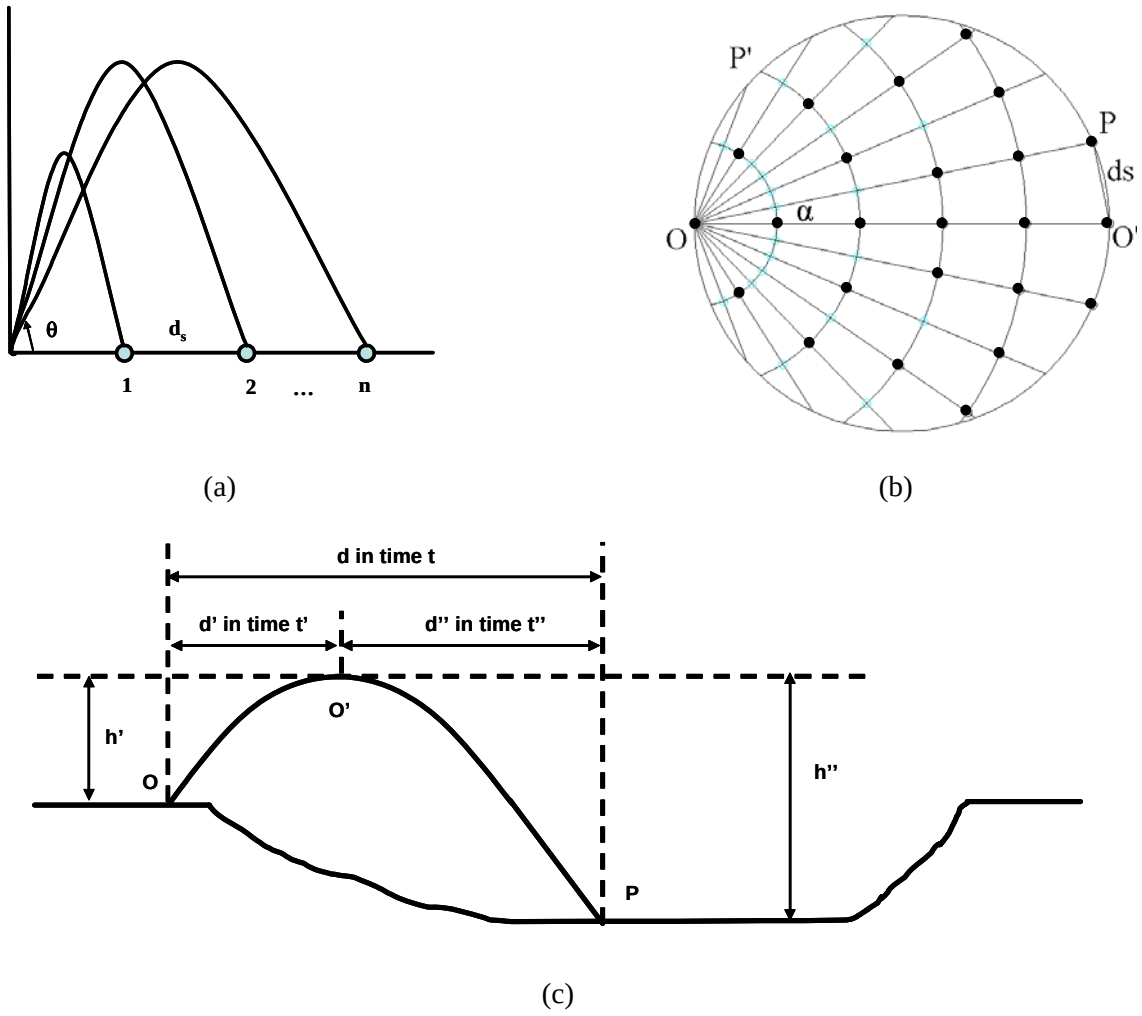
$$\phi = -Tan^{-1}\{(Tan^2\theta - \alpha \cdot Sec^2\theta)^{0.5}\}$$

Factor governing impact angle,

$$\alpha = \frac{3.244h}{v_{ij}^{\ 2}} \tag{15}$$

for a case when angles are same,

where v_i is launching velocity of sensor, θ is launching angle with horizontal, $j = 1,2,...,n$ and n is total number of sensors to be deployed. Depth of crater, impact angle, time of flight and distance travelled by sensors are shown in Figs. 7 (a) to 7 (d) for a typical parabolic launching strategy with varying launching angles and in Figs. 8 (a) to 8 (d) for a typical parabolic strategy with varying initial velocities.



(a) (b)

(c)

Fig. 6. (a) Geometry of sensors launching scheme, (b) topology showing number and positions of sensors in a typical circular sensing zone of 1 km diameter and (c) pictorial view of scheme at crater.

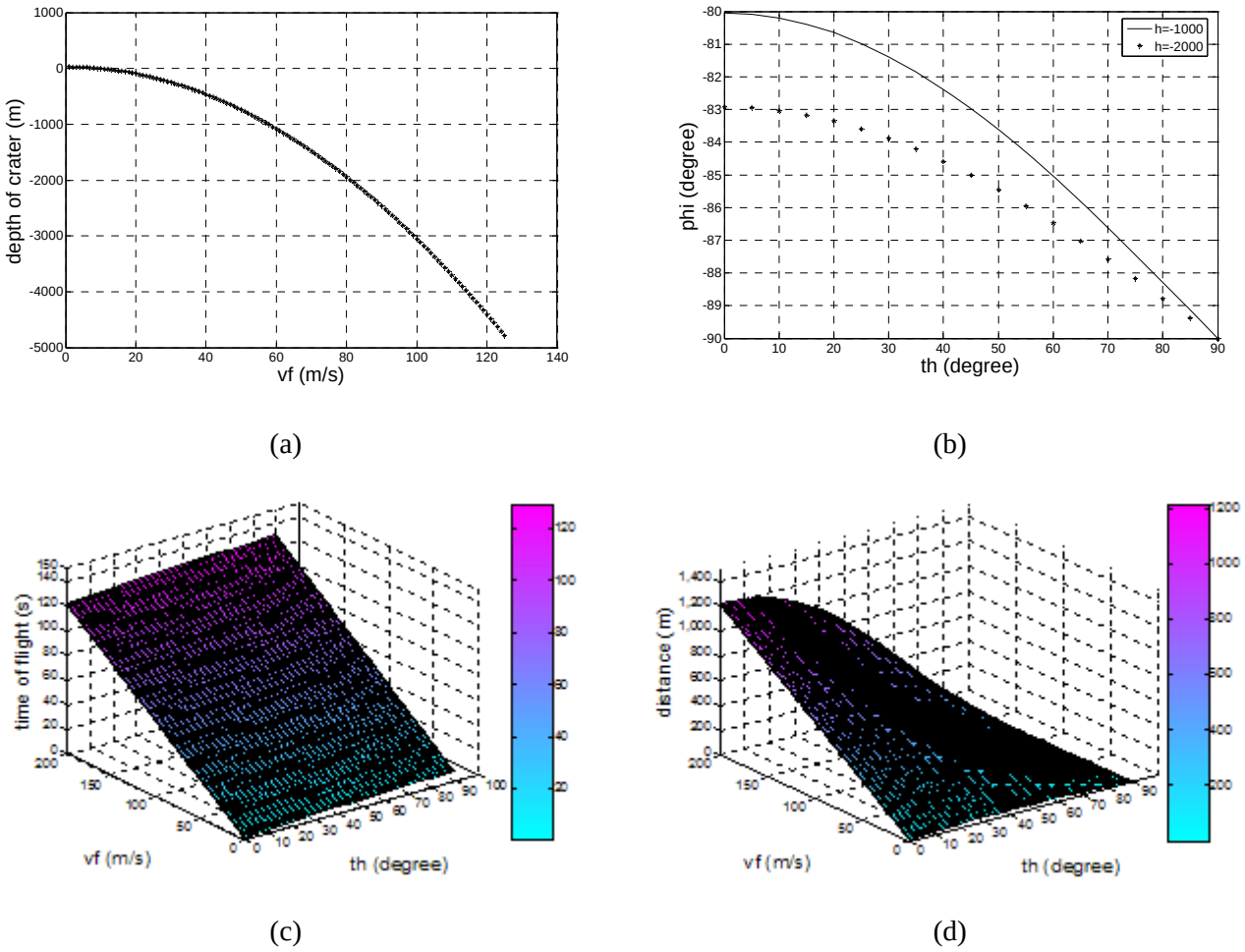


Fig. 7. (a) Depth of crater from the edge vs. impact velocity of sensor (v_i = 10 m/s); (b) Impact angle of sensor vs. launching angle (v_i = 10 m/s); (c) Time of flight of sensor vs. launching angle & impact velocity (h = - 1 km, v_i = 10 m/s); and (d) Distance of sensor vs. launching angle & impact velocity (h = - 1 km, v_i = 10 m/s).

For obtaining minimum number of sensors in case of both types of parabolic strategies, assume that the shooter is located at the left end of a diameter of a probing region or crater and it has to deploy sensors at an equal distance of d_s in a straight line having different angles α in horizontal plane as shown in Fig. 6 (b).

Here OO' is diameter and P is a point on semicircle. Therefore, $\angle OPO'$ is right angle and $Sin\alpha = \frac{d_s}{2R}$, where R is radius of sensing zone.

$\therefore \alpha = Sin^{-1}(\frac{d_s}{2R})$ is first horizontal angle for launching from the diameter on which shooter is located. Remaining angles are taken as multiple of α on both sides of diameter under consideration.

Length of chord is $OP = 2R \cdot Cos\alpha$. On this chord, sensors are to be deployed at an equal distance of d_s and number of sensors in this chord is given by length of chord divided by d_s. The longest chord is diameter under consideration and if shortest chord is considered with minimum length d_s then horizontal angle of this shortest chord is found as follows.

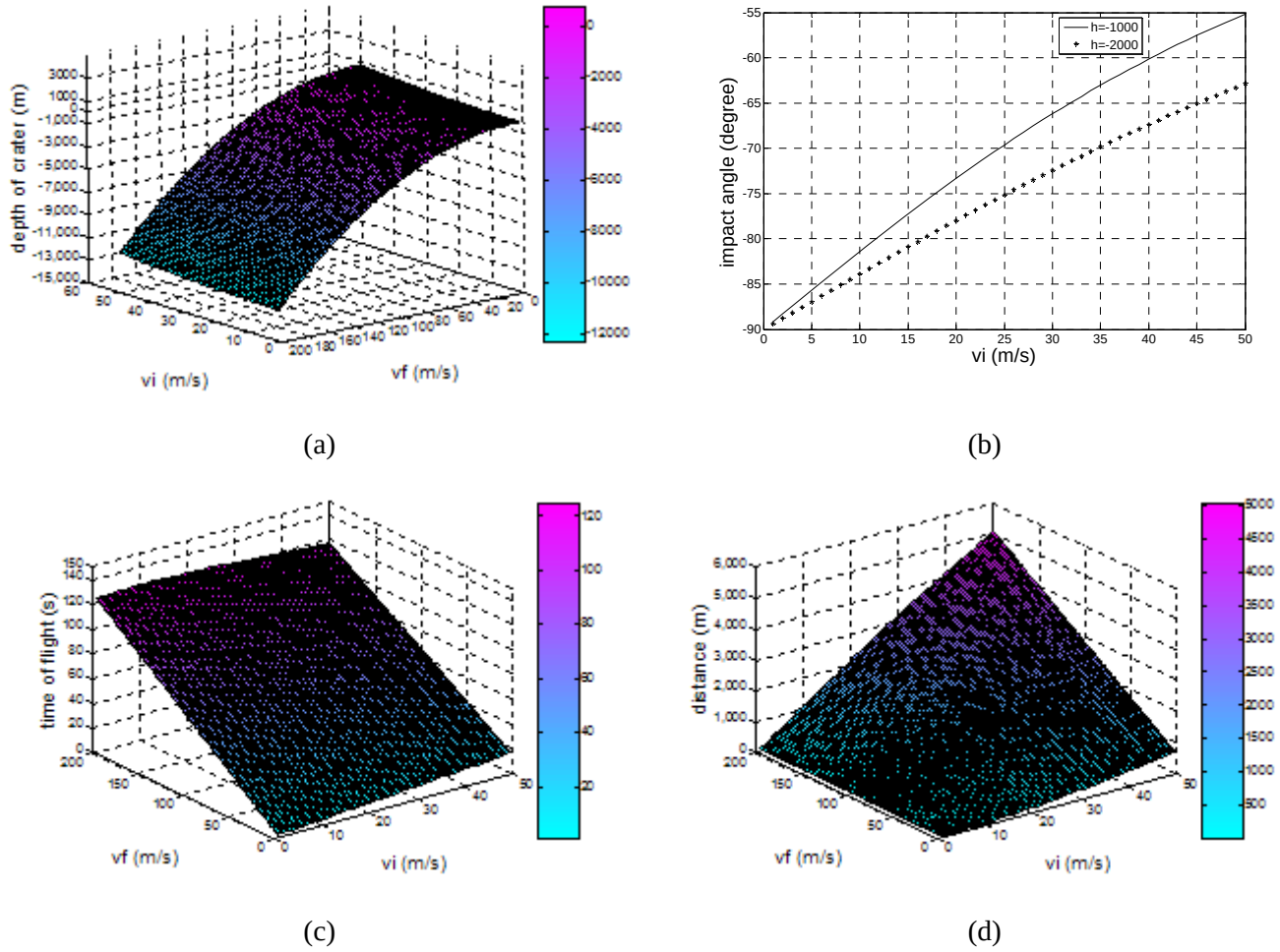


Fig. 8. (a) Depth of crater achieved by a sensor vs. launching & impact velocities, (b) Impact angle of sensor vs. launching velocity, (c) Time of flight of sensor vs. launching & impact velocities (h = - 1 km, θ = 30^o) and (d) Distance covered by a sensor vs. launching & impact velocities (h = - 1 km, θ = 30^o).

As length of shortest chord is d_s like OP' in Fig. 6 (b), horizontal angle made by this shortest chord with diameter is given by $\alpha' = Cos^{-1}(\frac{d_s}{2R})$ and considering setting of shooter for horizontal angles as multiple of α (i.e. $\alpha' = l \cdot \alpha$, where l is an integer), maximum value of integer l is given by

$$l_{\max} = floor[\frac{Cos^{-1}(\frac{d_s}{2R})}{Sin^{-1}(\frac{d_s}{2R})}], \tag{16}$$

where $floor[]$ is a MATLAB function which rounds the quantity in bracket towards minus infinity and it provides integer value of $l_{\max}$ or quotient of ratio in equation.

Total number of sensors for parabolic scheme is given by addition of sensors in each chord in either side of diameter.

$$\therefore n_p = \frac{1}{d_s} \cdot [\sum_{l=-l_{\max}}^{l_{\max}} 2R \cdot Cos(l \cdot \alpha)]$$

$$\therefore n_p = \frac{2R}{d_s} \cdot \sum_{l=-l_{\max}}^{l_{\max}} Cos[l \cdot Sin^{-1}(\frac{d_s}{2R})] = ceil[\frac{2R}{d_s} \cdot \sum_{l=-l_{\max}}^{l_{\max}} Cos\{l \cdot Sin^{-1}(\frac{d_s}{2R})\}] \ , \qquad (17\text{-a})$$

where ceil[] is a MATLAB function which rounds the quantity in bracket towards infinity and it provides integer number of sensors for a given probing region and wireless connectivity.

By observing deployment topology in Fig. 6 (b) critically, one can find that many sensors are redundant and redundancy is more near the shooter. We have checked various combinations of sensing zone and wireless connectivity and found that number of sensors after removing the redundancy becomes slightly more than half the number obtained from Equation (17-a). Therefore in practice, following Equation (17-b) may be used for finding minimum number of sensors which is obtained after removing redundancy.

$$\therefore n_{p_practical} \approx ceil[\frac{R}{d_s} \cdot \sum_{l=-l_{\max}}^{l_{\max}} Cos\{l \cdot Sin^{-1}(\frac{d_s}{2R})\} + 1] \qquad (17\text{-b})$$

Minimum number of sensors given by Equation (17-b) is 25 for zone with radius of 500 m. Maximum number of sensors is decided by weight permitted for payload. Fig. 9 shows practical minimum number of sensors from Equation (17-b) for a given zone of radius R and sensors having communication range d_s.

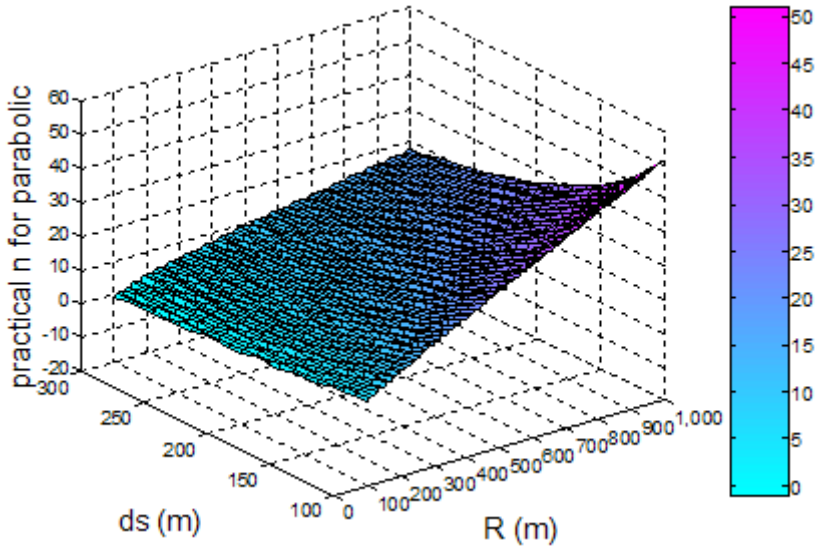


Fig. 9. Minimum number of sensors required for parabolic type scheme vs. radius of sensing zone (R) & wireless connectivity range (d_s).

In case of parabolic strategy also, there can be uncertainty in final position of sensors and they may settle at some practical positions instead of targeted positions due to irregular surface terrain. Suppose that location of mini launcher is selected as origin and targeted locations of deployed sensors are given

by vectors $R_{11}, R_{12}, ..., R_{1s1}$ for first setting of horizontal angle, $R_{21}, R_{22}, ..., R_{2s2}$ for second setting of horizontal angle,…., $R_{m1}, R_{m2}, ..., R_{msm}$ for m^{th} setting of horizontal angle where $s1, s2, ...sm$ in subscripts are number of sensors in $1^{st}, 2^{nd}, ..., m^{th}$ horizontal lines respectively and $s1 + s2 + ... + sm = n_{p_practical}$ as given by either Equation (17-b). Suppose, sensors attain actual positions as $R_{11} \pm \Delta_{11}, R_{12} \pm \Delta_{12}, ..., R_{1s1} \pm \Delta_{1s1}$ for first setting of horizontal angle, $R_{21} \pm \Delta_{21}, R_{22} \pm \Delta_{22}, ..., R_{2s2} \pm \Delta_{2s2}$ for second setting of horizontal angle,…, $R_{m1} \pm \Delta_{m1}, R_{m2} \pm \Delta_{m2}, ..., R_{msm} \pm \Delta_{msm}$ or m^{th} setting of horizontal angle, where Δ in subscripts indicate differences between targeted and actual positions of respective sensors. For any horizontal deployment line, maximum permissible difference between practical and ideal positions for any two adjacent sensors must be less than or equal to communication range d_s and for any two nearby sensors on two adjacent lines the permissible change is given by Equation (8) after using respective parameters.

5. Discussion

Deployment costs of all topologies depend on cost of sensor, number of sensors for a common sensing region and cost of deployment packet (for circular and spherical segment) or mini launcher (for parabolic). Deployment costs of all three are given by following equations.

$$C_c = n_c \cdot C_s + C_{c_packet} \tag{18-b}$$

$$C_{sp} = n_s \cdot C_s + C_{sp_packet} \tag{18-b}$$

$$C_p = n_{p_practical} \cdot C_s + C_{p_launcher}\ , \tag{18-b}$$

where C_s = cost of sensor;

C_c, C_{sp} and C_p are deployment costs for circular, spherical and parabolic respectively;

n_c, n_s and $n_{p_practical}$ are number of sensors for circular, spherical and parabolic respectively;

C_{c_packet}, C_{sp_packet} and $C_{p_launcher}$ are packet cost for circular, packet cost for spherical and cost of mini launcher.

Typically packet cost for circular, packet cost for spherical and cost of mini launcher in Equations (16-a) to (16-c) are constant and almost equivalent except some marginal difference, which indicates that deployment cost is directly proportional to number of sensors in each case. Considering a common circular sensing zone of 1 km in diameter, and neglecting constant components in Equations (18-a) to (18-c), deployment cost in all three cases are compared in Table 2 below.

Table 2. Comparison of deployment costs for three schemes.

Scheme	No. of Sensors (for R = 500 m)	Deployment Cost
Circular	16	16 C_s
Spherical	30	30 C_s
Parabolic	25	25 C_s

In case of circular strategy, when sensors reach on crater surface, they can form a circular topology. However, if any of the sensor node fails on impact, then connectivity of network would be lost. Possible solution to this problem is to double the number of sensors in a ring, so that even if a few sensors fail, remaining may be able to form network by their wireless connectivity. This option increases the redundancy by 100 %. In case of spherical segment deployment, the loss of connectivity problem on impact is solved to certain extent, as sensors are deployed in a grid fashion due to double ring structure and there are alternative routes for them to complete the communication link. To add further possibility of establishing a network, number of sensors can be doubled in each ring, which increases redundancy by 100 %.

Both, circular and spherical type deployments can only be adopted if rover has reached the lunar surface, has already settled and has become ready for its wireless operation (needed to complete communication link to orbiter). Otherwise, sensors deployed by these two methods can die due to short battery life time, before the rover has established and therefore become of no use. This necessitates release of sensor packet from the orbiter at a time when rover is ready for its wireless operation.

In parabolic deployment scheme, one can achieve enough radio coverage as there is a liberty to deploy sensor in desired direction by moving mini launcher in that particular direction. Moreover, a separate release of sensor packet from the orbiter is not required, since the rover must have settled and become ready for wireless operation before deploying the sensor nodes. Increase in redundancy is suggested here also, to increase probability of network establishment. In such a scheme, if lander (which actually carries rover with sensors and launcher) is landed at a place near to one of the interested lunar crater, then shooter can be mounted on lander itself instead of putting on rover. This reduces burden on rover to carry sensors and launcher to the edge of selected crater. Parabolic deployment scheme suffers from the disadvantage that either lander or rover needs more energy to carry the deployment mechanism and sensors. Also, it is seen that deployment cost in case of circular is lowest and that in case of spherical is highest, while that for parabolic is moderate. In planetary applications, where weight and power is not a serious issue, parabolic scheme seems a better choice as compared to circular or spherical segment schemes.

6. Summary

The deployment strategy for water ice sensors on the Moon is quite different than that used for terrestrial sensor networks. Suggestions are given to adopt the strategy for deployment of sensors on outer body like the Moon. Simulation results provide good understanding and more insight in to conditions of various parameters related to different topologies. Minimum numbers of sensors are derived based on optimization between maximum area coverage and wireless connectivity while deployment costs for all topologies provide quick information about selection of topology for a particular application.

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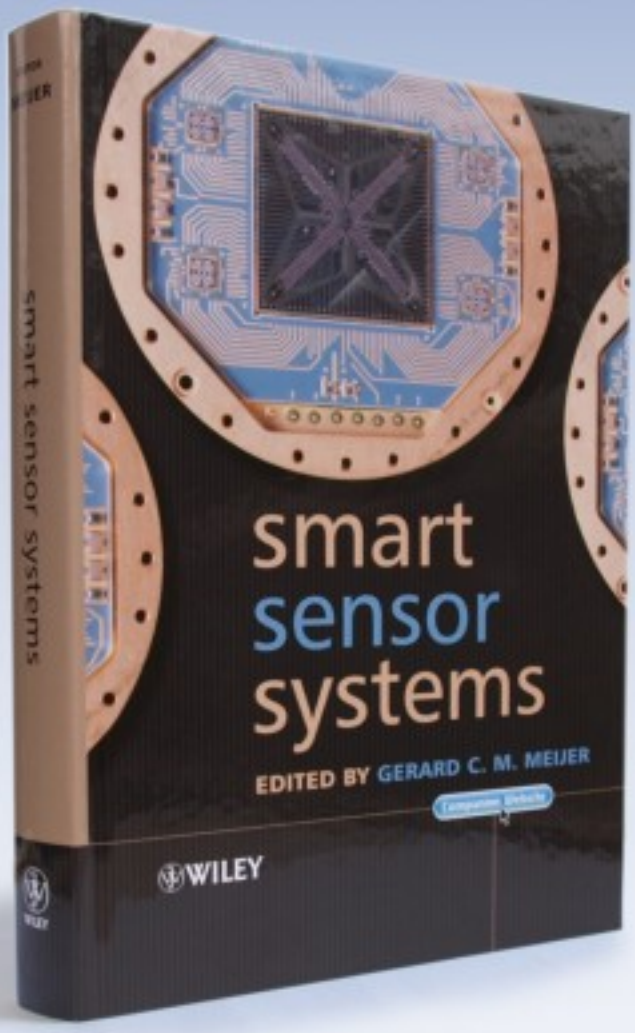

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