INVESTIGATION OF BUOYANT TRANSPORT SYSTEMS THAT EXPLOIT MARTIAN WEATHER PATTERNS

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Abstract

This research has demonstrated how Martian weather patterns can be used in balloon systems, incorporating autonomous navigation capabilities, to accelerate surface exploration. Polar transport of the primary atmospheric constituent, carbon dioxide, drives the planetary weather patterns, and nominal wind speeds are sufficiently high to facilitate planet-wide traverses. Seasonal variations cause changes in weather patterns in a predictable manner that can be exploited. These effects have been predicted using numerical simulations and verified when possible, starting with the Viking Landers and subsequently from rover and orbital spacecraft measurements. This research has utilized the Mars-GRAM weather simulation program to explore wind conditions over candidate surface launch locations throughout the Martian year. The data collected provides insight on desirable base locations and nominal launch opportunities for serial robotic balloon missions. It is possible to target a range of launch dates in order to reach selected downwind locations. For an expedition launching in the Northern hemisphere, the prevailing winds are east to west most of the year. However, near the summer solstice the prevailing winds reverse flowing from west to east for a short period. This change in flow direction is due to the sublimation of the polar ice caps. This effect and others provide a logical basis for navigation using atmospheric sounding techniques and buoyance control to effect navigation similar to sailing. Exploiting predictable weather variations can lead to exploration of vast areas of the planet or access to otherwise inaccessible locations.
The focus of this research is to develop a systematic approach for utilizing buoyant balloon platforms, launched from the surface of Mars, to transport rovers and other surface probes over great distances and to surface locations that cannot be reached from orbit.

Martian weather systems have been observed from Earth for well over 100 years. Changes in climate range from the polar ice caps to planet-wide dust storms\(^1\). For practical engineering level analysis of climatic conditions, physical measurement validation of the atmospheric models is needed. Beginning with the Viking landers, surface conditions on Mars have been measured. Since that time, numerous other surface exploration missions have measured local surface ambient conditions. However, this data is only representative of the lower few meters above ground level conditions. A more complete global climate model is required for numerous applications, including Martian planetary balloon systems\(^2\).

Over the past several months the balloon research conducted at Old Dominion University has focused on gaining an understanding of the basic Martian global weather processes. Primarily the work has been focused on learning how to use the Mars Global Reference Atmospheric Model (Mars-GRAM) computer program developed by NASA. Mars-GRAM is a FORTRAN code which implements various global climate models based upon user input scripts. The software is a reflection of the current engineering level understanding of the Martian climate.

Mars-GRAM is a very powerful tool for a wide range of applications. Different climate models are implemented over specific altitude bands and it is necessary to define the desired altitude interval for realistic simulations. In the present case, the NASA Ames Mars General Circulation Model (MGCM) is the controlling model. This circulation model is applicable in the 0 to 80 km altitude range. Mars-GRAM provides a wealth of output data, including local minute-by-minute wind vector predictions, temperature, pressure, and atmospheric conditions. The Mars-GRAM program includes a coarse resolution representation of the entire surface topography of the planet.

The Mars-GRAM code was requested and downloaded with approval from NASA in raw FORTRAN form. Time was spent learning to use a FORTRAN compiler on a UNIX computer to create a functioning program. Once compiled and operational the greatest problem was learning to effectively input the desired parameters. A great number of options were available for creating simulations, each activating a new level of sophistication to the climate model. There is continuing investigation on the proper use of some of the control parameters as part of this research. Mars-GRAM is capable of generating very large amounts of data. For example, data could be calculated for every second for one year at multiple surface locations. The data output is in a tabular format which is very conducive to post processing. MATLAB was used heavily to interpret the data numerically and graphically. Figure 1 is a representative MATLAB plot of local wind vectors at an altitude where balloon systems might operate. This plot demonstrates how local surface topography influences the calculation of wind vectors. Figure 1 is centered around a surface feature in the Acheron Fossae trough.

![Topographical Interactions: Wind Vector Plot](image)

**Figure 1: Wind Plot near Acheron Fossae Trough**

The atmospheric dynamics research to this point, has focused on seasonal influences on Mars.
atmospheric behavior. As mentioned previously, seasonal variations are easily visible, but the influence on balloon flight trajectories is unknown. Another complication is the irrelevance of the Gregorian calendar. Mars days and years are not related directly to terrestrial calendars. It is more useful to examine seasons based upon Mars orbit location and its local rotational inclination with respect to the sun. The common pseudo-time measure is the areocentric longitude of the sun, $L_s$. Similar to the inertial reference coordinates for Earth-based systems, the areocentric longitude divides Mars’ orbit into 360°, with each 90° interval corresponding to a season on Mars. By convention zero degrees corresponds to the vernal equinox in the Northern hemisphere, and progresses through summer solstice, autumnal equinox, and the winter solstice. The orbit of Mars is more elliptic than Earth, and its 1.881-year orbital period results in significant differences between seasonal atmospheric dynamics in the Northern and Southern hemispheres. Areocentric longitude is therefore the preferred method for incorporating planetary seasonal changes within the context of Mars-GRAM simulation histories.

Martian weather is controlled to a great extent by carbon dioxide transport between its poles. The Martian climate is actually more predictable than earth in some ways since terrestrial water transport is a controlling parameter on Earth and there are no oceans on Mars. Seasonal Mars polar imagery demonstrates the significant exchange of carbon dioxide as the polar ice caps sublimate and reform. Figure 2 graphically represents the Carbon Dioxide exchange at key seasons. The amount of carbon dioxide exchanged can be staggering—up to 33% of the total atmospheric mass can be deposited on the surface during winter.

Figure 2: Seasonal Carbon Dioxide Transport

My current research is exploring the use of these seasonal variations of carbon dioxide transport driven planetary winds as a reliable base for balloon flight trajectory design. Mars-GRAM has been used to examine balloon deployment scenarios from various locations on the planet over the course of several Martian years. These simulations were used to examine the repeatability of wind patterns for possible exploitation. Those data have produced exciting results. Figure 3 shows wind vectors at one of my somewhat arbitrary locations over several Mars years. While the plot looks like an ink blot test, it is important to note that there are two visible lobes. During most of the year, winds at that location blow from west to east (the nominal direction is 0° with an uncertainty range of approximately ±15°), but there is also a second, lower wind magnitude, lobe with a nominal direction of 210° ± 30°.
Figure 3: Vector Plot over Several Seasons

In Figure 4, only the nominal season changes are displayed as vectors. Notice there are a few (reduced magnitude) East to West wind vectors in this plot. When the data were examined, this general wind direction only occurs at a nominal Ls of 90°, or the summer solstice in the Northern hemisphere. This is the period of time when the polar caps sublime and atmospheric carbon dioxide concentrations increase. It seems there is a predictable pattern to this weather phenomenon which could be exploited by a planetary balloon for navigation.

Figure 4: Vector Plot at Ls=90 degree Intervals

A similar pattern was observed for atmospheric conditions at other altitudes. Figure 5 shows the vector plot of winds at 5 kilometers altitude. The primary difference is the magnitude of the wind velocity. The relation generally follows the rule that the higher the altitude, the higher the wind velocity. Similar altitude-dependent velocity profile histories were observed at all of the site locations examined thus far.

Figure 5: 5 km Altitude Seasonal Wind Variations

The understanding of predictable seasonal variations in weather is crucial for the successful navigation of autonomous aerial devices. However, global climate models are not sufficient to achieve the wind predictions and local conditions for engineering accuracy. An in situ measurement of the local conditions around a vehicle would allow an onboard climate model algorithm to be updated locally. This would allow the climate model to be experimentally verified while at the same time increasing accuracy of the autonomous navigation. A current technology with the capabilities for local flow field sensing is Light Detection and Ranging (LIDAR). LIDAR is similar to RADAR; however, laser light is used in sensing rather than radio waves.

LIDAR primarily works by sending out discrete beams of light and measuring the backscatter upon return to the instrument. The backscatter is affected by the medium in which the laser passes through. Atmospheric density and aerosol content of the medium are the primary factors influencing LIDAR measurements. In the case of Mars, atmospheric density is extremely low compared with Earth. A Mars LIDAR system...
would need to base its measurements on aerosol content of atmosphere. Since Mars atmosphere is always dusty, it should enable LIDAR systems to operate however this dust is very fine. Dust particles may be on the order of 1 μm in diameter or smaller. This small size along with the unknown nominal concentration of dust particles in the atmosphere may cause LIDAR measurements to become unusable. Sizing of the LIDAR equipment will be critical to the mission success. Balancing resolution requirements for the LIDAR and the equipment mass for balloon sizing is under study presently.

A local velocity field sensing instrument, such as a LIDAR system would allow real time autonomous navigation capabilities. The use of a ballast system would allow the balloon system to raise or lower its cruising altitude in order to effect changes in flight direction. The goal of this would be to sense the velocity above or below the craft, then change altitude and use the favorable winds at the appropriate height.

This research has shown great promise for using seasonal weather variations as a planning strategy in the development of autonomous navigation for Martian balloon transport systems. As the research continues, other important variables will be considered, including systems for active control of balloon altitude for improved navigation. A strong understanding of local weather conditions is crucial in the successful development of balloon transport capabilities. This research is focused on demonstrating a compelling basis for incorporating balloon systems which exploit local weather, by incorporating active balloon guidance to navigate and conduct science for accelerated near-term Mars exploration.
References


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