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SATELLITE CONSTELLATIONS FOR ATMOSPHERIC SOUNDING WITH GPS: A REVOLUTION IN ATMOSPHERIC AND IONOSPHERIC RESEARCH

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ABSTRACT

Spaceborne GPS atmospheric science is now blossoming, with small missions in preparation in several countries. These missions require high performance GPS flight receivers with capabilities well beyond most space needs. The full promise of spaceborne GPS science can be realized only with dedicated constellations of orbiting GPS receivers specially designed for science use. Initial proposals are for a pilot constellation of a dozen or so microsats launched at once into a single orbit plane. In the future we may see a large constellation of hundreds of tiny satellites, each with a mass of less than 1 kg, enveloping the earth in multiple orbit planes. This will require advances in spaceborne GPS receiver architecture and microsatellite design. Key tasks include reducing a high performance receiver to a 1.5-watt, credit-card size instrument; devising efficient 3-axis stabilization for microsats; and providing low-power cell phone communication from space, There will be a sizable commercial payoff to this work. The miniature receiver will have enormous appeal as both a flight instrument and a high end terrestrial receiver for surveying, geodesy, and aircraft applications. Moreover, the commercial value of atmospheric data for use in weather prediction could one day be substantial.

INTRODUCTION

With the maturing of the Global Positioning System and the appearance of increasingly affordable spaceborne receivers, GPS usage is expanding rapidly into the world of space flight projects. Indeed, owing to the great utility and convenience of autonomous onboard positioning, timing, and attitude determination, basic navigation receivers are coming to be seen as almost indispensable to future low earth missions. This development has been expected and awaited since the earliest days of GPS. Perhaps more surprising, however, has been the emergence of direct spaceborne GPS science and the blossoming of new science. applications for high performance geodetic space receivers.

Science applications of spaceborne GPS include centimeter-level precise orbit determination to support ocean altimetry; Earth gravity model improvement and other enhancements to GPS global geodesy; high resolution 3D ionospheric imaging; and atmospheric limb sounding (radio occultation) to produce precise profiles of atmospheric density, pressure, temperature, and water vapor distribution. Figure 1 offers a simplified summary of the Earth science now emerging from spaceborne GPS.

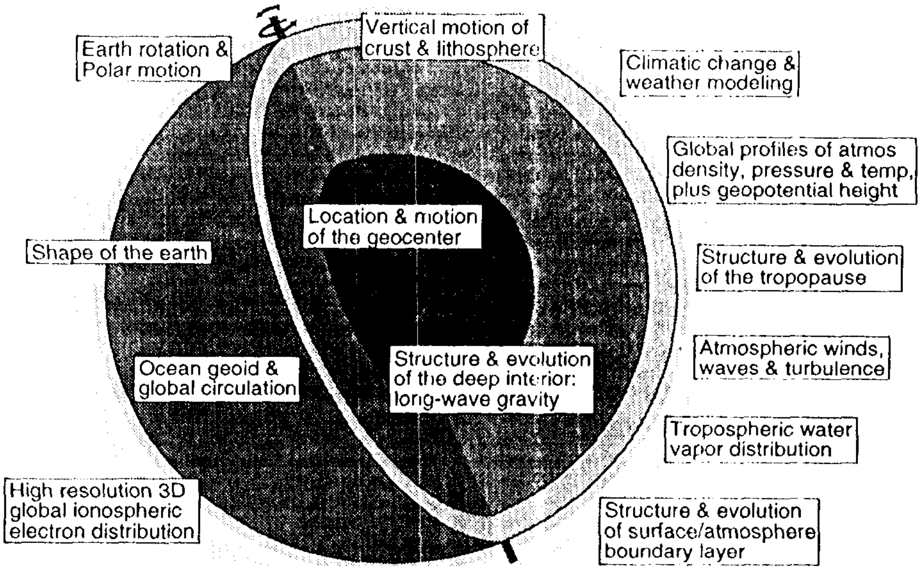


Fig. 1. Some key science applications for a spaceborne array of GPS receivers.

At present, Earth science from spaceborne GPS is derived front just two missions. The first is the U.S.-French Topex/Poseidon mission, launched aboard an Ariane rocket in August 1992, which carries a six-channel, dual-frequency, P-code receiver developed by Motorola. The GPS antenna on Topex/Poseidon provides a nearly hemispherical field of view directed towards the zenith, affording no view of the Earth's limb and thus no view of the atmosphere and little view of the ionosphere. Over the past three. years, GPS data from Topex/Poseidon support will be found to make this idea a reality, And while the initial step is likely to be modest--a pilot constellation of perhaps 12 satellites- –we foresee that within a decade up to several hundred tiny 1-kg microsats will be in place providing a vast flow of data that will transform the study of the earth's climate, weather, and ionosphere. In the following sections we summarize the techniques of atmospheric and ionospheric sounding and describe our vision of the development of a large constellation of orbiting receivers.

GPS ATMOSPHERIC OCCULTATION

Background

The probing of planetary atmospheres by radio occultation dates to the early 1960s when Mariners 3 and 4, viewed from Earth, passed behind Mars [4,5]. in this technique-a radio signal from a spacecraft moving behind a planet is tracked until blockage. As the signal cuts through the planet's refractive atmosphere, its lengthening path delay, revealed by its changing phase delay or Doppler shift, can yield a precise profile of the atmospheric density, pressure, temperature or water vapor, and, to some degree, composition and winds. Amplitude variations can expose atmospheric turbulence and wave structure.

While radio occultation has probed many planets and moons throughout the solar system, it has as yet found no useful application to Earth, for two reasons. First, the observation requires both a radio source and a suitable receiver off the planet, outside the atmosphere; seldom have we had such matched pairs in Earth orbit. Second, to be of use in studying Earth's atmosphere, whose nature we know well, such measurements must be continuous, comprehensive, synoptic. We therefore need many transmitters and receivers aloft at once, densely sampling the global atmosphere every few hours. Until the arrival of GPS and low cost microsats, the evident cost of such an enterprise made it impractical within Earth science programs.

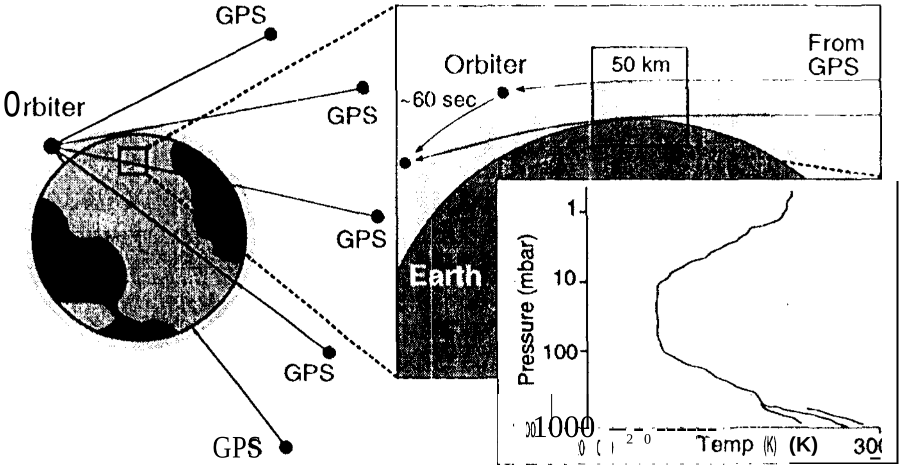


Fig. 2. Illustration of atmospheric temperature profiling by GPS occultation

in the late 1980s, a group at JPL proposed observing GPS signals from space to make atmospheric soundings by radio occultation, as shown in Fig. 2 [6]. Briefly, the observed Doppler shift in the GPS signal induced by atmospheric bending permits accurate estimation of the atmospheric refractive index. From that one can retrieve, in sequence, profiles of the atmospheric density, pressure, and temperature (or, if we model temperature, water vapor in the lower troposphere) with high accuracy (<1 Kelvin in temperature) and a vertical resolution of better than 1 km [7,8]. Figure 3 shows the predicted accuracy of atmospheric temperature profiles as a function of altitude, based on extensive simulation studies performed at JPL. Notice that in the lower part of the troposphere, the uncertainty in water vapor content, particularly in the tropics, leads to a large error in the recovered temperature. in that region, since it is water vapor that is generally of greater consequence in weather modeling, it becomes advantageous to supply nominal temperature lapse rates derived either from independent measurements or from standard models and instead recover water vapor profiles.

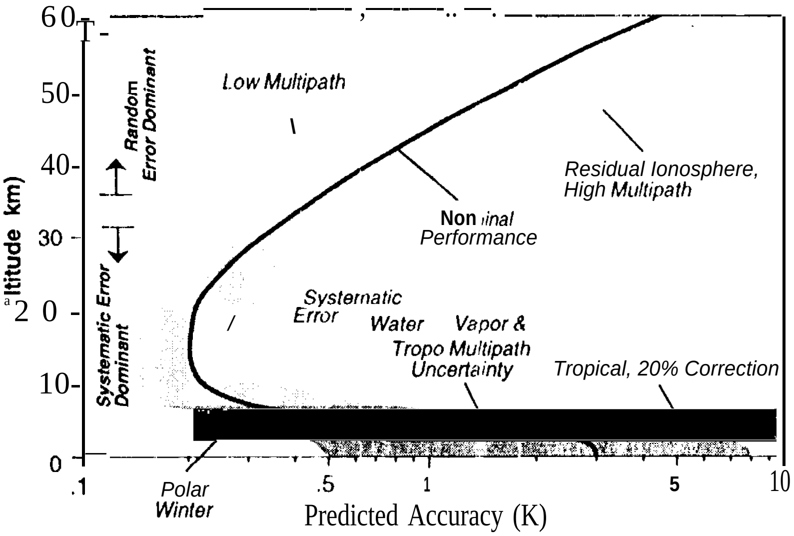


Fig. ..?. Estimated GPS-derived atmospheric temperature accuracy vs altitude.

A single satellite can recover more than 500 profiles each day, distributed almost uniformly around the globe; a large constellation would recover many thousands of profiles, which could one day have a profound impact on both long term climatological support stations, and feeds a steady stream of data back to the ground, Many hundreds of occultation passes have now been acquired and analyzed. Figure 4 shows a typical temperature profile computed at JPL, along with nearby radiosonde measurements for comparison, For a more comprehensive presentation of results from this experiment see Refs. [3] and [9].

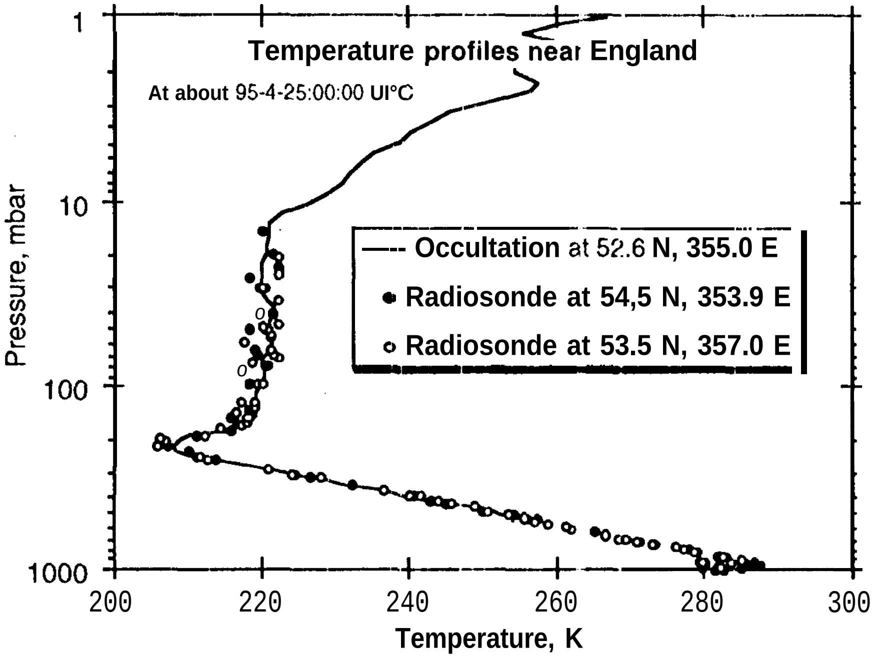


Fig. 4. Typical GPS atmospheric temperature profile compared with two radiosondes.

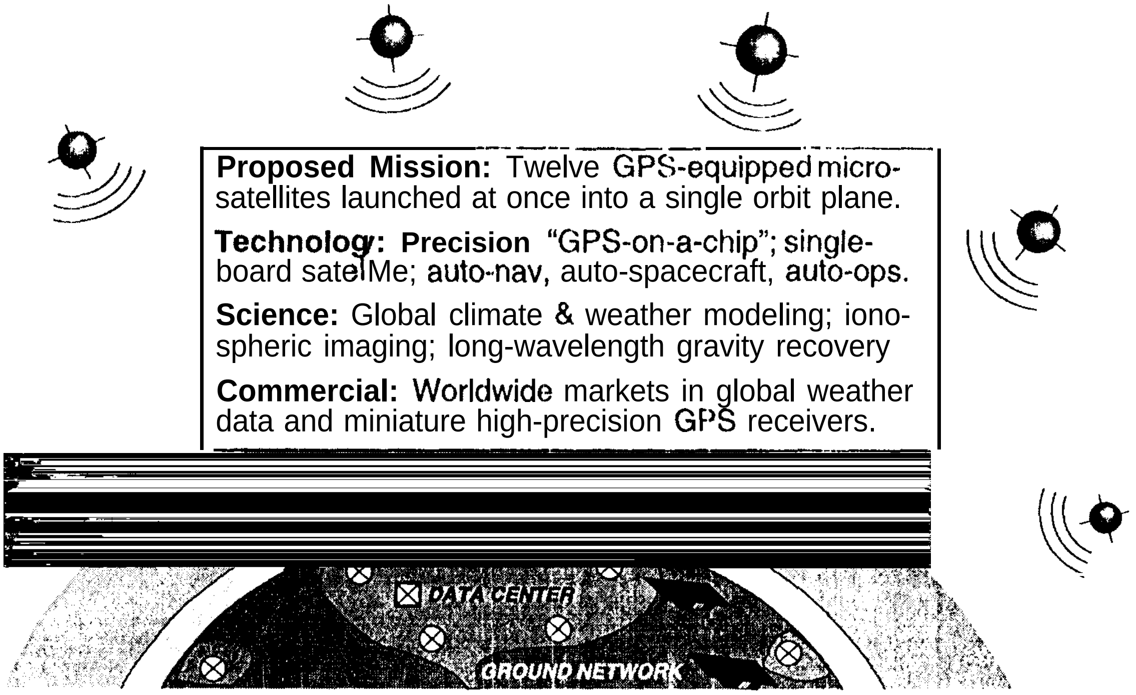
The best occultation data are acquired with P-code tracking during the occasional periods when encryption is off, and JPL has been able to negotiate several such periods, lasting typically a few weeks each, with the Department of Defense. Initial profiles recovered by groups at JPL, UCAR, and the University of Arizona are extremely encouraging, in many cases with estimated accuracies of about 1 Kelvin over a wide range of altitudes [9], This performance is expected to improve steadily as analysis refinements are introduced, ionospheric. studies with the GPS/MET data are just now beginning and as yet no results have been reported.

IONOSPHERIC IMAGING WITH SPACEBORNE GPS

The dual-frequency GPS signals offer a direct means of measuring the integrated or total electron content (TEC) along the line of sight slice through the ionosphere to provide exquisite vertical resolution; combined data from large numbers of space- and ground-based receivers will enable the creation of high-resolution two- and three-dimensional snapshot images of the global ionosphere [13].

Simulation studies described in Ref. [13] dramatically demonstrate the value of space-based GPS data in ionospheric imaging. With ground data alone, virtually nothing of the vertical electron distribution is revealed; with space data alone, high quality vertical and horizontal images arc recovered. Combining space. and ground data provides finer detail and overall resolution, however, the improvement over purely space-based data is rather slight. This is because in addition to providing the vertically slicing cuts needed to recover vertical information, the space links cross one another over a much wider range of angles, supplying much of the information needed for a full image.

The impact of spaceborne GPS imaging on ionospheric science will be profound, The ionosphere is a complex, mutable matrix containing an assortment of transient, inhomogeneous structures, including troughs, waves, bulges, plumes. ‘l’he dynamic behavior of the midlatitude trough, for example, is related to magnetospheric constellations. These include Iridium, Globalstar, Orbcomm, Odyssey, and INMARSAT-P, the largest of which (Iridium) will comprise 66 satellites. While this remains a possibility (and presents one of the least expensive options), none of the major constellation now in development has as yet offered to carry such a receiver (though they've been asked) and their commercial focus on global telecommunications makes that prospect unlikely anytime soon.



Proposed Mission: Twelve GPS-equipped micro-satellites launched at once into a single orbit plane.

Technology: **Precision** "GPS-on-a-chip"; single-board satellite; auto-nav, auto-spacecraft, auto-ops.

Science: Global climate & weather modeling; iono-spheric imaging; long-wavelength gravity recovery

Commercial: Worldwide markets in global weather data and miniature high-precision GPS receivers.

Fig. .5. Concept for a pilot constellation of spaceborne GPS receivers for Earth science,

The most attractive alternative, and the one we have studied most closely, is to devise a small satellite that can be packed in relatively large numbers (say, a dozen) into the small spaces allotted to secondary payloads on various launchers. In some cases, for example, the Delta-2 launcher built by McDonnell-Douglas, a secondary payload can be orbited simply for the cost of integrating the payload onto the booster, which includes the cost of various levels of safety and compatibility testing. According to sources at McDonnell-Douglas, for a simple payload on the Delta-2, this cost could be in the neighborhood of $1M.

Figure 6 illustrates one concept we have put together to take advantage of the Delta-2 or similar launch opportunity. We have essentially sliced a roughly 30-cm cube into six flat microsats, each with two fold-out "wings" for solar power. Each satellite would have a phased array GPS antenna fore and aft with significant gain directed towards the Earth limb to observe both rising and setting occultations. A small GPS receiver capable of tracking 12 dual-frequency signals at once would serve as the only science instrument; it would also provide the real time satellite state, timing, and attitude information needed to maintain orientation and to schedule high rate occultation observations autonomously. Attitude would be controlled to within 5° (all that's required) by a combination of a small reaction wheel and magnetic torquing. Ground communication would be either through a direct low-power downlink or by a phone link through a high-orbiting telecom satellite. These small satellites could be built with relatively minor enhancements to current technology (for example, miniaturizing a reaction wheel). The latest generation TurboStar receiver now under development will meet the size, mass, and functional requirements while consuming about 5 watts. Planned upgrades will soon reduce this to less than 4 watts. Total power consumption for each satellite would be less than 12 watts.

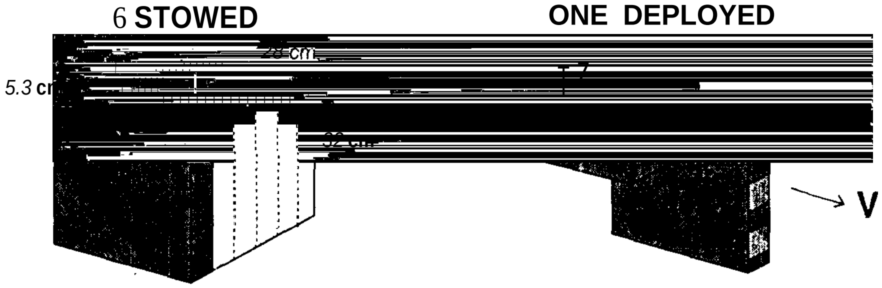


Fig. 6. Microsat concept for low-cost deployment of a pilot Space GPS Array.

One could easily pack 12 such microsats into one of the slots for secondary payloads on the Delta-2. The basic idea is to bundle them together on the booster and deploy the package as a single unit. The containment mechanism would then give way and a simple spring release would impart small relative velocities to the satellites, which, over a period of months would disperse and randomize around the orbit plane. In concept they would be fully autonomous "fire-and-forget" sensors requiring no tending from the ground. (In practice, some uplinking, for example, of software upgrades, can be expected with the pilot system.) Within a few minutes of deployment, the onboard GPS receivers would determine everything the satellites need to know to fix their orientations and to plan and carry out a full program of science observations indefinitely. We estimate that by adopting a low cost commercial grade approach to parts selection and a NASA “Class D“ reliability standard, the microsats could be built for about $250K each, including about $50K for each flight receiver. The estimated total cost for deploying a 12-satellite pilot array, including development and launch, is roughly $ 15M.

A Large Array for the New Millennium

While the proposed pilot array will be of enormous research value for climatologists, weather modelers, and ionospheric physicists (among, others), and while it could do much to advance the technology for autonomous microsatellites, it is far less than is needed to realize the full operational potential of spaceborne GPS science. Global weather prediction, for example, places inordinate demands on observation and modeling. For spaceborne GPS atmospheric data to have an appreciable (and beneficial) effect on weather prediction, they must encompass the globe with extremely high density and high time resolution. The same is true for imaging the global ionosphere at high resolution in three dimensions. This, of course, implies a lot of satellites. Scientists at JPL estimate that at least 100 satellites will be needed to usefully enhance weather prediction (the possibility of which has yet to bc demonstrated), with probable additional benefits up to 500 or 1000. Such numbers are daunting and may seem entirely impractical, But by applying and extending the approach we used to restrain the projected cost of the pilot array, wc find that such a possibility y is not so far-fetched.

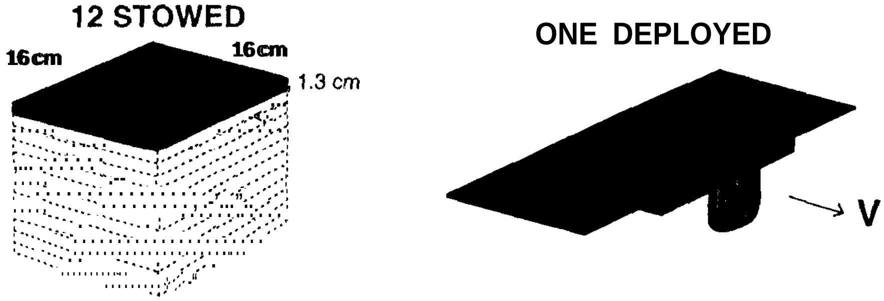


Fig. 7. Nanosat concept for a low-cost 100+ element Space GPS Array.