A History of GPS Sounding

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ABSTRACT

The roots of GPS sounding go back to the first days of interplanetary flight. In the early 1960's teams from Stanford University and the Jet Propulsion Laboratory exploited radio links between Earth and the Mariner 3 and 4 spacecraft to probe the atmosphere and other properties of Mars. Radio science has since been a staple of planetary exploration. Before the advent of GPS, application of radio occultation to Earth was deemed impractical, and it was not immediately evident that even GPS could be usefully adapted. Techniques devised for geodesy in the 1980's, including "codeless" carrier reconstruction, clock elimination by double differencing, GPS-based precise orbit determination, and compact, low-cost receivers, set the stage. JPL submitted the first GPS occultation proposal to NASA in 1988. Though that "GPS Geoscience Instrument" did not fly, it established the concept and led soon to the GPS/MET experiment, conceived by the University Corporation for Atmospheric Research and sponsored by the US National Science Foundation. The remarkable success of GPS/MET has led NASA to mount follow-on experiments on five international missions, launching between 1999 and 2001. Those will refine the systems and techniques of GPS sounding, setting the stage for COSMIC—the first operational GPS occultation constellation.

(Key words: COSMIC, GPS Sounding, atmospheric limb sounding, atmospheric occultation, radio occultation, Global Positioning System, GGI, GPS/MET, Oersted, Sunsat, CHAMP, SAC-C, GRACE, JPL, UCAR, Stanford)

1. INTRODUCTION

Predictions, like pioneering space missions, can be risky, and for the moment we can not be certain how this venture in GPS occultation known as COSMIC will play out. But of this

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there can be little doubt: The fortunes of COSMIC will do much to determine the course of spaceborne GPS science generally, and if those fortunes attain their promise the history of GPS sounding as told in 20 years will largely begin with the mission now before us. Indeed, it is a rare undertaking of any kind that can offer such sweeping consequences. Should COSMIC succeed, it will transform the way we approach atmospheric remote sensing. The ubiquitous signals from GPS, together with Russia's GLONASS, Europe's Galileo, and a host of planned commercial and military craft in high orbits will become illuminating beacons enveloping the earth. Development inspired by a COSMIC success will give rise to low-cost miniature occultation sensors and automated data systems that will open the door to a rapid expansion. The emerging constellations of low earth orbiters (LEO's), with platforms soon to number in the hundreds, will be poised to host these sensors at almost negligible marginal cost, to the potential profit of their shareholders and the lasting benefit of earth system science.

A few years after the completion of COSMIC we can expect to be acquiring 100,000 or more occultation soundings each day, yielding a horizontal sampling resolution of better than 100 km. This will bring dramatic improvements to operational weather analyses and enable for the first time "snapshot" 3D imaging of the global ionosphere. As occultation sensors become ubiquitous on "Big LEO" arrays, horizontal resolution may reach the 50 km twice-daily goal cited in NASA's 1998 "Easton Report" (unpublished) as the ultimate desired for initializing global weather models.

Now and then there arises a kind of chance convergence of disparate threads that brings an opportunity so rich, so felicitous and rewarding, that it should not be allowed to pass. Today by good fortune we see the almost concurrent emergence of every element vital to a new global enterprise in GPS sounding: copious high beacons at nearly ideal frequencies bathing the globe; great constellations of low orbiters equipped with GPS receivers and designed, conveniently, for instantaneous global data transfer; low-cost microelectronics of staggering power; and the occultation technique itself—the most precise and arguably the simplest spaceborne atmospheric probe yet devised. The range of science payoffs, which spans disciplines from meteorology and climatology to ionospheric physics, space weather, geodesy, and physical oceanography, eclipses that of nearly every other earth sensing technique. Figure 1 depicts some of the science pursuits in which COSMIC and its successors will have a decisive impact. This compelling alignment of forces is occurring, moreover, at a time when the emergence of commercial data markets could, with the impetus of a COSMIC success, give rise to extensive occultation arrays deployed entirely at private expense. We are at a time of transition in atmospheric remote sensing and COSMIC sits at the nexus; a success here could well change everything.

Though GPS sounding is the newest entry in atmospheric sensing from space, it is in a sense the most primitive. Today's arsenal of techniques—microwave radiometry, passive infrared, solar occultation, active lidar—depend ultimately on atomic-level phenomena: principles firmly rooted in 20th century physics. By contrast, GPS occultation rests on such classical pillars as elementary optics, thermodynamics, gas laws, and electromagnetism, all developed well back in the 19th century or before. Though it has taken modern technology and the space program to transform these foundations into practical systems for remote sensing, the technique itself could have been readily grasped 150 years ago.
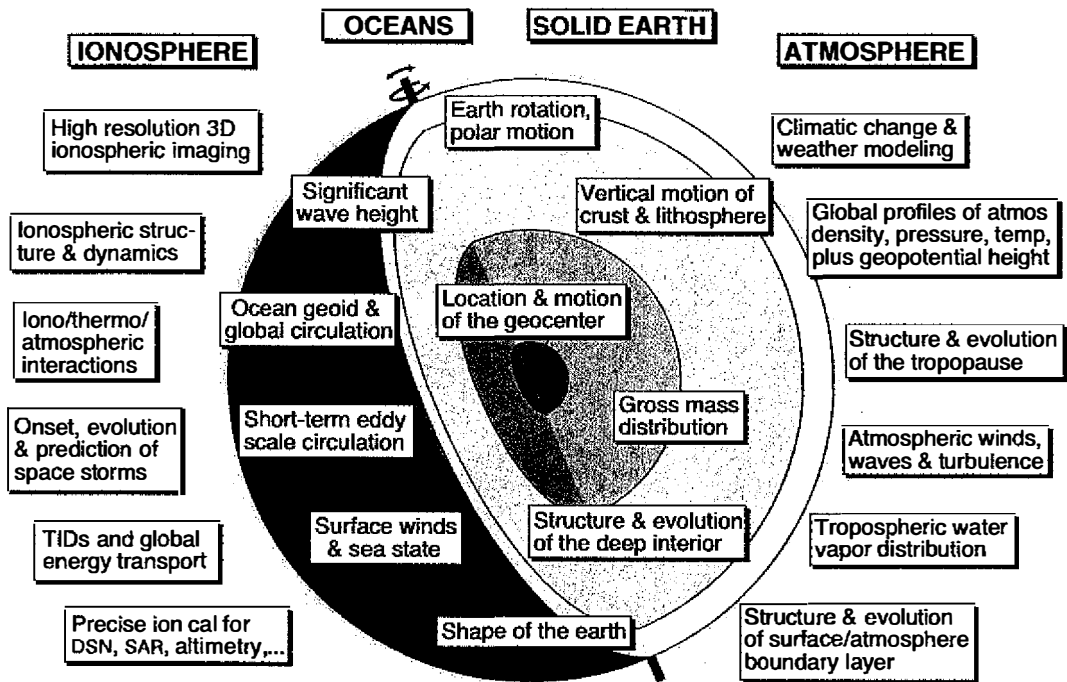
Fig. 1. Examples of the diverse areas of Earth science in which COSMIC and other spaceborne GPS missions will have a significant impact.

It was the more surprising, therefore, that as scientists began to examine GPS as a tool for atmospheric sensing in the late 1980's they found it offered so many attractions not found in the established space techniques. Here is a partial list:

- Compact, low-power, low-data-rate sensors, costing of order $300K rather than millions or tens of millions, easily embedded in spacecraft large and small
- An ability to sound the atmosphere from the stratopause to the earth's surface
- A vertical resolution of a few hundred meters in the troposphere, compared with several kilometers or worse with other space instruments
- Self-calibrating profiles that never drift, can be compared between all occultation sensors over all time, and provide a calibration standard for other sensor types
- Virtually unbiased measurements that can be averaged over days or weeks to yield normal points with an equivalent temperature accuracy of order 0.1 K
- Fully independent measurement of pressure and height, permitting recovery of absolute geopotential heights and derived winds with no external reference
- The prospect of concurrently sampling the full global atmosphere at low cost

• An extraordinary diversity of applications outside of atmospheric science

2. EARLY HISTORY

The idea of atmospheric radio occultation emerged in the early days of interplanetary flight. Scientists seeking to extract the most from fleeting flyby encounters noted that as a spacecraft passed behind a planet, its radio links would be systematically refracted by the atmosphere. They then began devising ways to deduce atmospheric properties from the observed effects, which include the Doppler shift, attenuation, and scintillation. An account of these early efforts is given in Melbourne et al. (1994). The first relevant proposal came from a group at Stanford University in 1962, in preparation for NASA's Mariner 3 and 4 missions to Mars. The Stanford group had developed a one-way observing system exploiting the radio instruments aboard the early Mariner spacecraft to monitor charged particles and plasma in interplanetary space. In this approach, a dual-band phase-coherent signal was sent from Earth to the spacecraft where the differential phase, which is strongly affected by the presence of charged particles, was measured and sent back to Earth in the data stream. The 1962 Stanford proposal would have used this technique during encounter to probe the Martian ionosphere and surface properties (Fjeldbo, 1964). Because the one-way technique is limited by oscillator instabilities at both the transmitter and the receiver, it was expected that phase drifts in the spacecraft oscillators would mask the slight refraction effects of the thin neutral atmosphere on Mars.

The Jet Propulsion Laboratory, meanwhile, had developed a two-way coherent Doppler tracking system in the late 1950's for navigating spacecraft to the moon and nearby planets. In this technique a signal is sent to the spacecraft where it is coherently retransmitted (after a small frequency shift) to Earth for detection and measurement (see, for example, Melbourne, 1976). In this case, only the earth-based oscillator, which can be of the highest quality, comes into play. In 1963 the JPL group independently proposed to probe the Martian neutral atmosphere by the more precise two-way occultation technique (Kliore et al., 1964). This was chosen by NASA for Mariners 3 and 4 and in 1964 a joint experiment team combining the Stanford group (focusing on the ionosphere) and the JPL group (focusing on the neutral atmosphere) was formed. Thus began a pioneering collaboration lasting more than 20 years, which established "radio science" as a mainstay of planetary exploration. In the mid 1960's, the Stanford-JPL team introduced the Abel inversion technique (Fjeldbo and Eshelman, 1968; Fjeldbo et al., 1971) in which the observed bending angle induced by the atmosphere is tapped to recover precise refractivity profiles (Kursinski et al., this issue). Abel inversion has been the foundation of occultation analysis ever since (though, owing to the great observing strength of GPS, Abel may soon give way to more generalized inversion methods that combine multiple observations). Radio occultation has now probed the atmospheres of nearly every planet in the solar system and many of their moons, and revealed properties of planetary surfaces and ring systems as well (e.g., Kliore et al., 1965; Fjeldbo and Eshelman, 1968; Fjeldbo et al., 1971; Eshelman, 1973; Lindal et al., 1983; Tyler, 1987; Lindal, 1992). Figure 2 shows a sample of data taken during the occultation of Voyager 2 by Uranus in the late 1980's.
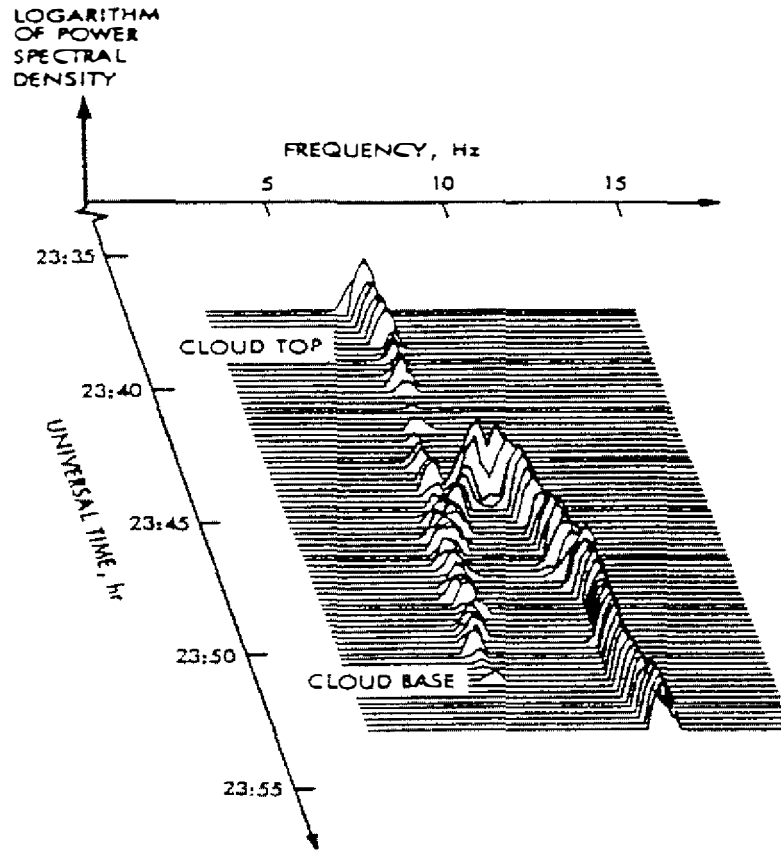
Fig. 2. Sequence of power spectra made of open-loop data acquired from Voyager 2 while occulting behind Uranus. Structure in lower troposphere gives rise to multiple received frequencies.

It is something of an irony that radio sounding has been applied fruitfully for decades everywhere in the solar system—except on Earth. The reasons for this are not hard to find. First, a proper occultation requires both a transmitter and a receiver off the planet of interest; seldom in the past have we had such matched pairs near Earth. More significantly, to be of value in studying our own atmosphere, which we know intimately, such measurements must be comprehensive, continuous, synoptic. We require many transmitters and receivers aloft at once, densely sampling the global canopy every few hours. There were in fact suggestions as far back as the 1960's for adapting the occultation technique in a limited way to Earth (Fishbach, 1965; Lusignan et al., 1969) but, as noted by Kursinski in his 1997 doctoral dissertation, the extensive required infrastructure implied a cost "exceeding the level of interest." It is a further irony that what a short time ago was dismissed for its evident impracticality now appeals in part for its promise of unequalled economy. By fortunate happenstance the many-billion-dollar investment in basic infrastructure has been made for other reasons; and the occultation sensor—little more than a special purpose digital processor—is not only inexpensive but is

becoming almost universally required (in slightly reduced form) for navigation and timing on low earth satellites.

3. DAWN OF THE MODERN ERA

Even after the impending arrival of GPS became generally known in the late 1970's there was a considerable lag—about a decade—before the occultation possibilities were recognized. This may seem curious when we consider that (1) GPS was conceived at the outset for use in low earth orbit (Parkinson, 1976); (2) the idea of earth orbiting occultation had already been advanced several times by 1970; (3) the solid earth science community had begun touting GPS as a potential centimeter-level geodetic system as early as 1978; and (4) planetary occultation, as we have seen, was seized upon at the earliest possible moment, even before the basic data analysis concepts had been devised.

There were several reasons for this delay. By the 1970's a variety of "conventional" atmospheric sensing techniques were in development and there was no strongly felt need within the science community for something more. Perhaps more significantly, GPS and its mode of operation did not easily fit the occultation paradigm developed for planetary science, and practicing radio scientists did not readily perceive the possibilities. GPS is a strictly one-way observing system, which, as we saw in the planetary example, appears to imply a need for stable oscillators at all transmitters and receivers. It was known that although GPS would fly atomic clocks, the signals would be intentionally destabilized for "unauthorized" users in a process known as "selective availability." This appeared to imply a need for costly classified receivers and operations, if permission could be gained at all. In addition, during a planetary occultation the signal phase modulation is either removed, leaving a pure carrier, or kept well below $90°$ so that a strong carrier component remains. GPS signals, by contrast, are always fully phase-modulated ($\pm90°$) with ranging codes, resulting in a so-called "suppressed carrier" (i.e., no carrier line in the spectrum). Although technical solutions to recovering the GPS carriers, even without knowledge of the codes, are straightforward, this presented early conceptual barriers to those who regarded GPS as strictly a code-based, meter-level ranging system. For the occultation task, *millimeter* precision would be needed. There was further concern that the precise modeling of receiver motion required for accurate retrievals would tax the state of the art in orbit determination for a low Earth orbiter. Finally, planetary occultations employ highly directional antennas at both ends to maximize signal strength and reject external and reflected signals. The wide GPS beams and the nearly omnidirectional antennas typically adopted in receivers, while adequate for meter-level positioning, seemed ill-suited to the demanding occultation task. Instrument designers faced the prospect of a clumsy and costly "bouquet" of steerable high-gain antennas on each sensor.

It was the pioneering work of GPS geodesists in the early and mid 1980's that put these issues to rest. By 1987 it was known (within a small community) that unclassified "quasi-codeless" receivers with broad-beam antennas could recover dual-frequency GPS phase with the requisite millimeter precision, and that a strategy of concurrent observing from multiple sites would permit "double differencing" and related techniques (Wu, 1984) to eliminate se-

lective availability and other clock errors. It was then a small step to see that analogous techniques could be applied directly in occultation processing to remove clock errors (Kursinski et al., this issue). It thus emerged that the one-way GPS observing constraint, which at first seemed to demand stable clocks everywhere in the system, could be artfully adapted through concurrent observations to eliminate stable clocks altogether. This enabled both accurate retrievals and a reduction in instrument cost. Moreover, it was becoming clear that the basic techniques of GPS geodesy could be extended to provide few-centimeter orbit determination for any low earth orbiter (Yunck et al., 1985), easily adequate for occultation data analysis. As has happened repeatedly in this undertaking, a fortuitous unfolding of events, unimagined in the original system concepts, combined to make the seemingly prohibitive almost trivial, but it required a new way of approaching the occultation problem. In the end, what appears under the original radio science paradigm to be a clutter of near-fatal liabilities can, by ingenuity and good fortune, be arranged into a self-correcting whole of elegant simplicity.

4. THE GGI PROPOSAL

By 1987 all elements were in place to crystallize this vision, but a seed in the form of a perceived need was still lacking. In another stroke of fortunate timing, NASA announced in mid-1987 a major new Earth science initiative: a long-term observing program that would become "Mission to Planet Earth" (now "Earth Science Enterprise"). The centerpiece was to be a series of massive earth satellites known as the Earth Observing System (EOS) devoted to the study of our planet as a complex, interdependent whole—a pursuit known as Earth System Science. In cooperation with other international space agencies NASA issued an open call in Dec 1987 for new instrument concepts. This came to the attention of one of us (Yunck), who headed a GPS geodesy group at JPL. A proposal team was formed in January 1988, seeking broad earth science applications for a spaceborne GPS receiver, dubbed the GPS Geoscience Instrument (GGI). The team, consisting largely of geodesists, had little initial enthusiasm for atmospheric sounding. In March, Yunck approached Dr. Gunnar Lindal, a leading planetary radio scientist at JPL who, under the name Fjeldbo, had been a principal on the Stanford team that proposed the first planetary occultation experiment in 1962. Taking into account the latest techniques of GPS geodesy, Yunck supplied Lindal with a breakdown of expected GPS phase measurement errors (thermal noise, multipath, high order ionosphere) and within a few hours Lindal reported that we could expect to measure stratospheric and upper tropospheric temperatures to about 1 K, with a vertical resolution of about 1 km.[4] In a memo dated 15 March 1988, possibly the first written pronouncement on the subject, Lindal wrote:

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[4]For completeness we should record that in late 1987, unknown to the GPS team, a planetary radio science group was also contemplating an EOS occultation proposal. Their concept employed the high gain TDRSS antennas aboard each EOS spacecraft to conduct two-way soundings through the geosynchronous TDRSS satellites, effectively transplanting the interplanetary paradigm to earth orbit. In early 1988, when the two groups became aware of one another, the TDRSS team changed their approach to GPS occultation. But, unfamiliar with GPS carrier reconstruction and other calibration techniques, the team assumed code-based one-way ranging and, even with aggressive SNR assumptions, estimated limiting temperature accuracies of about 7 K. The proposal was not submitted.

In the ionosphere, the refractivity data yields the vertical electron density distribution. Below approximately 50 km altitude, the refractivity may be used to determine the density, pressure, and temperature distribution in the stratosphere and upper troposphere. (The air density in the mesosphere is too low to permit reliable measurements.)

Near the top of the stratosphere, the altitude resolution of the profiles will be 1.5 km, as measured by the height of the first Fresnel zone. At the surface, the vertical resolution will vary with the meteorological conditions in the regions probed by the links, but will typically be about 0.5 km. The corresponding horizontal resolution longitudinal to the link will range from 200 km to roughly 100 km over the same altitude interval. Scaling of previous results from Titan indicates that it should be possible to determine the temperature near the tropopause to an accuracy of about 1 K.

Note that the refractivity profiles do not uniquely define the vertical changes in both the composition and temperature of the lower troposphere. In order to determine density, pressure, and temperature profiles from the radio data in this region, it is therefore necessary to obtain the water vapor distribution from another source.... Conversely, if the temperature profile is available from other instruments, one can use the refractivity profile to compute the vertical distribution of water vapor. (Lindal, 1988)

This accurately captures our understanding and expectations today. Lindal quickly computed refined estimates of the expected temperature accuracy at several levels in the atmosphere, from which a curve of projected accuracy was created. Figures 3 and 4, taken from the 1988 GGI proposal, illustrate the occultation concept and the projected temperature accuracy as a function of altitude. Compare Fig 4 with the far more detailed analyses of Kursinski et al. in this issue.

Also in March 1988, another of us (Liu, then at the University of Illinois) joined the GGI team to develop the ionospheric science portion of the proposal. In another example of serendipity, Dr. Liu and his colleagues had just published the first papers introducing the concept of "ionospheric tomography": imaging the ionosphere in 2 and 3 dimensions with multiple observations of earth satellite links (Austen et al., 1988). This was an idea ripe for exploitation by the rich harvest of ionosphere-piercing dual frequency signals GGI would collect. In addition, Dr. William Melbourne of JPL, with a diverse background in astronomy, geodesy, radio science, and navigation, was tapped as Principal Investigator.

Recognizing the value of an array of receivers, the GGI team proposed to place instruments on all US EOS platforms, the European EOS platform, and the International Space Station—the maximum allowed under the EOS call. In February 1989, the GGI proposal was approved in full and it appeared that NASA was on track to deploy the first GPS occultation constellation. Over the next three years, however, the EOS program confronted drastic cutbacks and restructuring, and in 1993 GGI was dropped. But by then the idea had been aggressively promoted among international science agencies and throughout the earth science community (Yunck et al., 1988; Yunck and Melbourne, 1989; Melbourne et al., 1994). While there was resistance within parts of the atmospheric science establishment, scattered groups of advocates and creative new flight initiatives, several involving tiny microspacecraft, were beginning to appear in the US, Europe, and elsewhere.
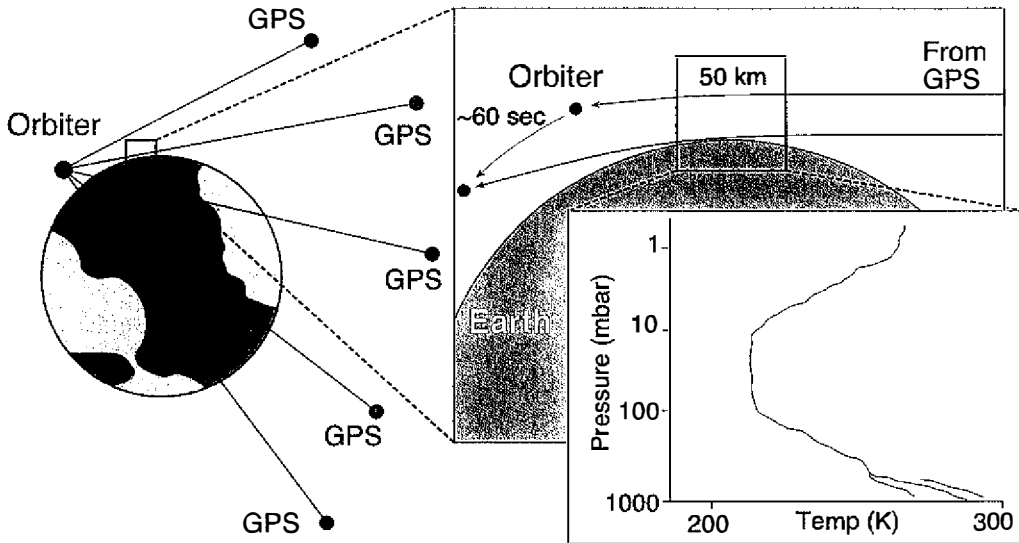
Fig. 3. Conceptual illustration of GPS atmospheric occultation (from 1988 GGI proposal).
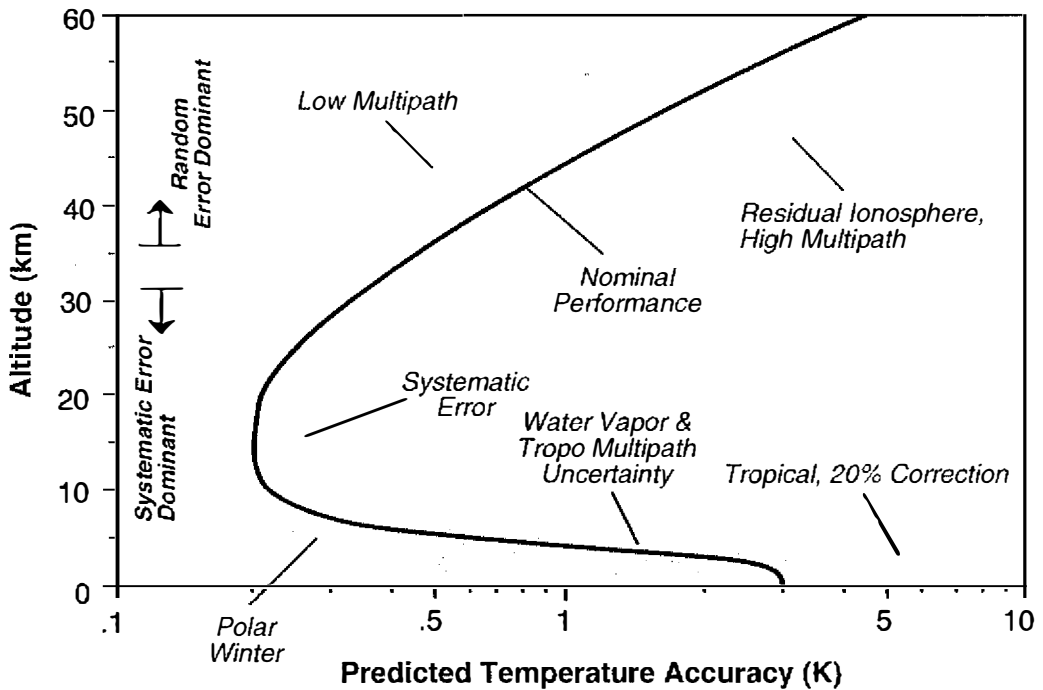

Fig. 4. Early estimate of expected temperature accuracy vs. altitude with GPS occultation (from 1988 GGI proposal).

5. THE RISE OF GPS/MET

At this point the focus shifts to the University Corporation for Atmospheric Research (UCAR) in Boulder, Colorado, and to their sponsoring agency, the US National Science Foundation. In 1991, a group at UCAR (which had also been involved in geodetic and other scientific uses of GPS), including Randolph Ware, Michael Exner, and Ying-Hwa Kuo, saw the promise of GPS occultation and swiftly put together a mission concept and a proposal to the NSF. The idea was to place a low-cost GPS ground receiver, adapted for occultation and ruggedized for flight, on an orbiting platform of opportunity to demonstrate the technique in space. The NSF responded with enthusiasm, UCAR brought in the US National Oceanic and Atmospheric Administration, the Federal Aviation Administration, and Orbital Sciences Corporation as co-sponsors, and almost overnight GPS/MET was born. In April of 1995 the GPS/MET instrument was launched by a Pegasus rocket into low earth orbit aboard NASA's MicroLab I spacecraft (Fig. 5). The instrument was adapted from a commercial version of JPL's TurboRogue geodetic receiver, built by Allen Osborne Associates; the software was modified for flight by JPL. The GPS/MET science team included Drs. Chris Rocken and

Fig. 5. Artists rendering of NASA's MicroLab I spacecraft which carried the GPS/MET occultation experiment. The occultation antenna is on the right side; receiver is immediately behind.

Xioalei Zou of UCAR, Prof. Benjamin Herman and his colleagues at the University of Arizona, and Drs. S. Sokolovskiy and M. Gorbunov of the Russian Institute of Atmospheric Physics, where GPS radio occultation inversion techniques have been studied since 1987 (Gurvich and Krasil'nikova, 1987). A parallel analysis effort was conducted at JPL under NASA sponsorship. The JPL team, which developed separate analysis systems, included Drs. E. R. Kursinski, George Hajj, Stephen Leroy, and Larry Romans. A typical temperature profile from GPS/MET is shown in Fig. 6. For more on GPS/MET see Anthes et al. (this issue) and references therein.

As is now known throughout the world, GPS/MET has been an unqualified success (Ware et al., 1996; Rocken et al., 1997) and has beautifully set the stage for what is soon to come. But GPS/MET was a limited first step. The flight instrument was adapted quickly from an early geodetic unit and offered only a primitive codeless capability. This meant that it could acquire high quality data only during brief intervals when the Air Force turned off GPS signal encryption, which is normally on continuously. In addition, only a single low-gain antenna directed towards the limb was provided to acquire both occultations and all GPS data for orbit determination, limiting both the occultation signal quality and orbit accuracy. Perhaps most significant, the receiver possessed virtually no special tracking software to cope with the weak and erratic signals passing through the dense lower troposphere. Consequently, signal tracking frequently failed at altitudes of 3-5 km, particularly in the tropics and mid-latitudes where water vapor is prominent and the thermal structure complex. Nevertheless, analysis of the unique GPS/MET data set has provided not just pioneering atmospheric science but enormous
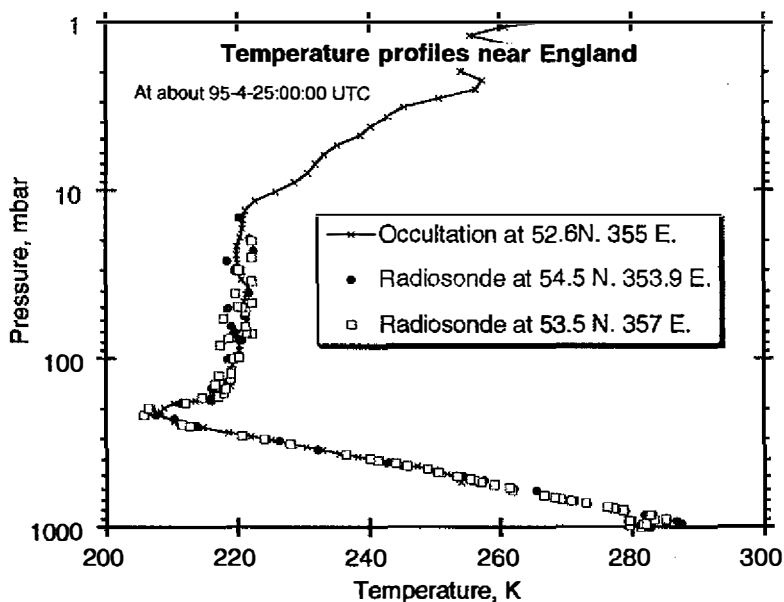

Fig. 6. Early temperature profile from GPS/MET revealing sharp tropopause near England. Nearby radiosonde measurements are shown for comparison.

insight into the behavior of occulted signals and the requirements for tracking them—knowledge that has been exploited in the design of the next generation of occultation receivers.

The COSMIC instrument will feature high-gain antennas tailored to the occultation task, pointing in both the forward and reverse velocity directions, together with separate upward-pointing broad-beam antennas to acquire data for orbit determination; an enhanced codeless technique—the most advanced yet developed—which will provide data quality during signal encryption surpassing that of GPS/MET with encryption off; adaptive tracking loops to better maintain lock in the problematic lower troposphere; and a unique "open-loop" acquisition method, pioneered on Voyager (Fig. 2), to assure capture of all perceptible occultations down to the earth's surface, even when signal lock cannot be maintained. The GPS/MET effort has also led to the creation of sophisticated, automated data analysis systems which, with further improvements for COSMIC, will be suited to the most demanding occultation data challenges.

6. THE IGS REFERENCE NETWORK

Another major legacy of GPS geodesy is the extensive GPS ground network that has provided the needed reference data to GPS/MET and will serve COSMIC and other future occultation missions. In the mid and late 1980's, GPS geodesy was conducted exclusively on an episodic or "campaign" basis, with receivers carried to the field for temporary data collection. By the early 1990's, falling receiver prices had made permanent networks feasible, and in 1992 the International GPS Service for Geodesy (IGS) was formed to oversee the deployment and operation of a permanent global network to provide precise GPS orbits and reference data to geodesists (Mueller and Beutler, 1992). By the time of the GPS/MET launch in 1995, a network of about 100 permanent sites was in place, funded entirely by geodetic interests, collecting precise reference data every 30 seconds and returning them daily. To properly remove selective availability "dither" for occultation data analysis, reference data at 1-sec intervals is required. Before the GPS/MET launch, JPL modified the receiver software at six of the IGS sites to deliver 1-sec samples; that was essentially the only expense incurred by GPS/MET to acquire ground reference data.

Today the IGS oversees a thriving network of over 250 sites worldwide, many of them returning data every hour. A joint effort by NASA and the German space agency is upgrading 20 of those sites to provide 1-sec data in near real time for several upcoming GPS occultation flights (see below). This high rate sub-network will provide ample redundancy to assure a supply of reference data for nearly all possible occultations. The IGS recently expanded its formal charter to encompass support for GPS data acquired from low earth orbit. The high rate network will continue to be maintained to support occultation and spaceborne GPS science generally. (We might note that the GPS Joint Program Office has announced that selective availability may be turned off before 2007; if that occurs, the sample rates needed for occultation reference data will be relaxed by about a factor of 10.) While COSMIC and other missions will be expected to contribute to its operation, the infrastructure is in place, the procedures and protocols established, and the marginal cost to future users will be relatively small.

7. THE NASA FLIGHT EXPERIMENTS

The pre-COSMIC history of GPS sounding does not end with GPS/MET. Next in line is a series of five NASA-sponsored experiments on a diverse mix of international flights of opportunity. Inspired by the pioneering example of GPS/MET, NASA agreed in 1995 to sponsor occultation receivers on two tiny international flight projects: Denmark's Ørsted mission, designed primarily for magnetic field mapping, and South Africa's Sunsat, a student-built satellite carrying a high-resolution imager. These were both provided with GPS/MET-class occultation receivers and were launched together aboard a Delta rocket in late February of 1999. After lengthy spacecraft checkout periods, limited data sets began arriving in September 1999. Because of antenna constraints on these small spacecraft, and continuous GPS signal encryption, the data quality is considerably lower than for GPS/MET. This is not entirely a bad. Though the data will be of limited science value, the experiments will further hone analysts' abilities to work with demanding occultation data sets. In addition, the Sunsat instrument can be upgraded in flight to improve its codeless tracking performance and test open-loop tracking algorithms. The Ørsted and Sunsat missions are depicted in Fig. 7.
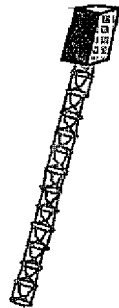
A glimpse of the future of GPS occultation will come from the next two missions: SAC-C (Fig. 8), an Argentine spacecraft carrying a multispectral imager and magnetometer, and CHAMP (Fig. 9), a German mission for magnetometry and gravity mapping. These much

Fig. 7. Overview of Ørsted and Sunsat microsat missions launched in February 1999.
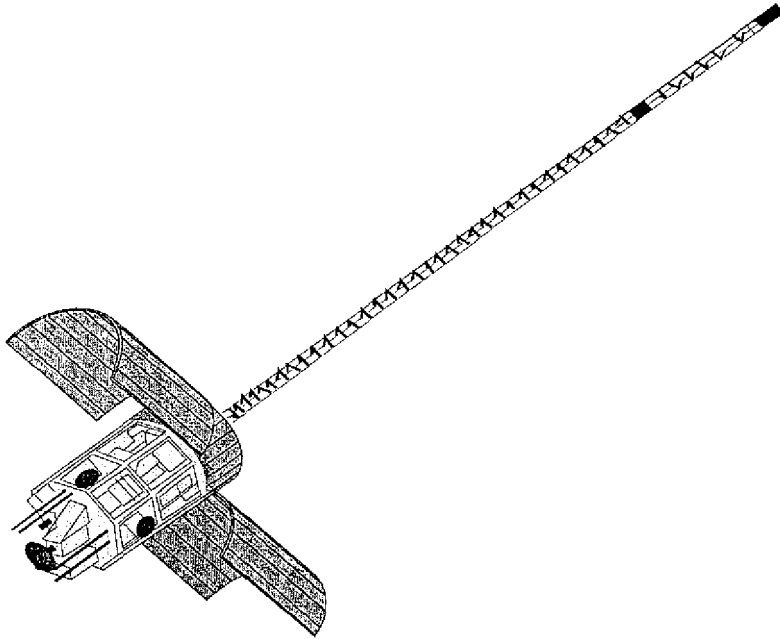
Fig. 8. Illustration of the Argentine SAC-C spacecraft. GPS antennas fore and
aft will capture rising and setting occultations. A down-looking antenna
will seek to capture GPS ocean reflections.

larger spacecraft are due to be launched separately in the summer of 2000 and will carry the
first examples of JPL's next-generation occultation receiver. Known as the BlackJack, this is
the prototype for the COSMIC receiver. SAC-C will be the first to carry occultation antennas
in both the fore and aft velocity directions, and will thus be the first to observe rising occulta-
tions. Both will feature more directional occultation antennas (7-10 dB gain) and both will
carry down-looking antennas in an attempt to recover GPS signals reflected from the ocean
surface. All flight software can be modified and reloaded after launch. For several years, then,
CHAMP and SAC-C will serve as developmental test beds for GPS sounding. In space, this
will allow experiments with enhanced codeless acquisition techniques, adaptive tracking loops
during weak signal conditions, and open-loop sampling. On the ground, the data will be used
to test robust editing techniques, advanced retrieval algorithms, calibration and validation sys-
tems, and fully automated end-to-end analysis systems.

Finally, NASA will place occultation receivers on the twin GRACE spacecraft, now set
for launch in mid-2001. GRACE is one of the first of NASA's Earth System Science Path-
finder (ESSP) missions and is jointly sponsored by the German space agency DARA. The two
spacecraft will fly in formation, 170-270 km apart (Fig. 10), performing precise satellite-satel-
lite ranging (accomplished by a modified BlackJack) to generate detailed maps of the earth's
time-varying gravity field. In addition, the lead spacecraft will capture rising occultations
while the trailing spacecraft will acquire them as they set. Together they will form the func-
tional equivalent of a single COSMIC spacecraft.

While it is unlikely that Ørsted and Sunsat will survive long into the era of CHAMP, SAC-C, and GRACE, the latter three taken together, should they all succeed, will offer us the first semblance of a pilot constellation. Though not optimally arrayed nor well adapted to "operational" use, they will afford a great deal of experimentation and preparation before the COSMIC launch. By that time the low-troposphere acquisition and retrieval techniques will be well advanced, and the end-to-end data acquisition and analysis systems will be poised for immediate high-volume, near-real-time production. The sequencing of these steps could hardly be improved.
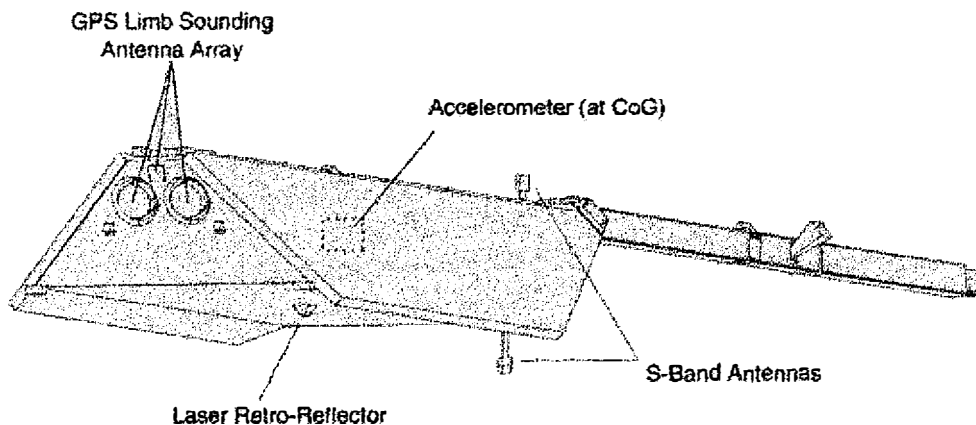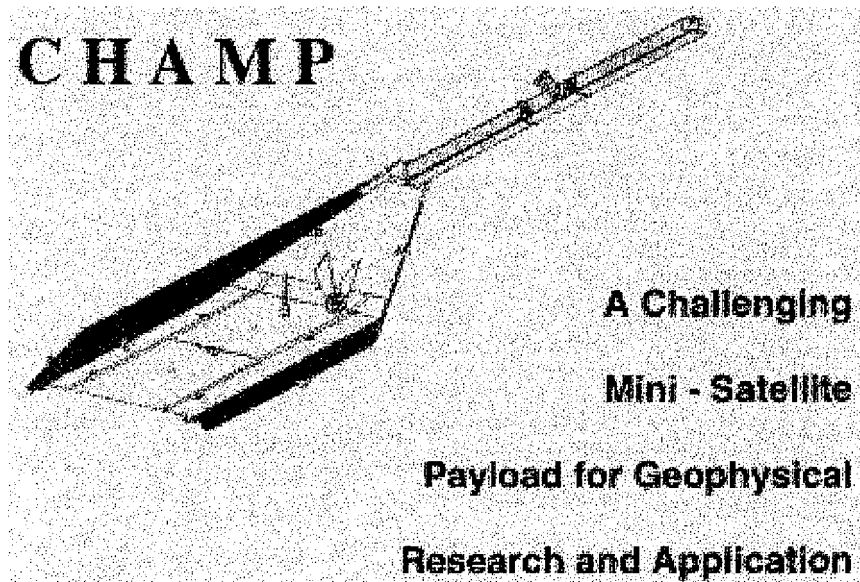

Fig. 9. Illustration of the German CHAMP spacecraft. Two aft-looking GPS antennas will capture setting occultations. A down-looking antenna will seek to capture GPS ocean reflections.
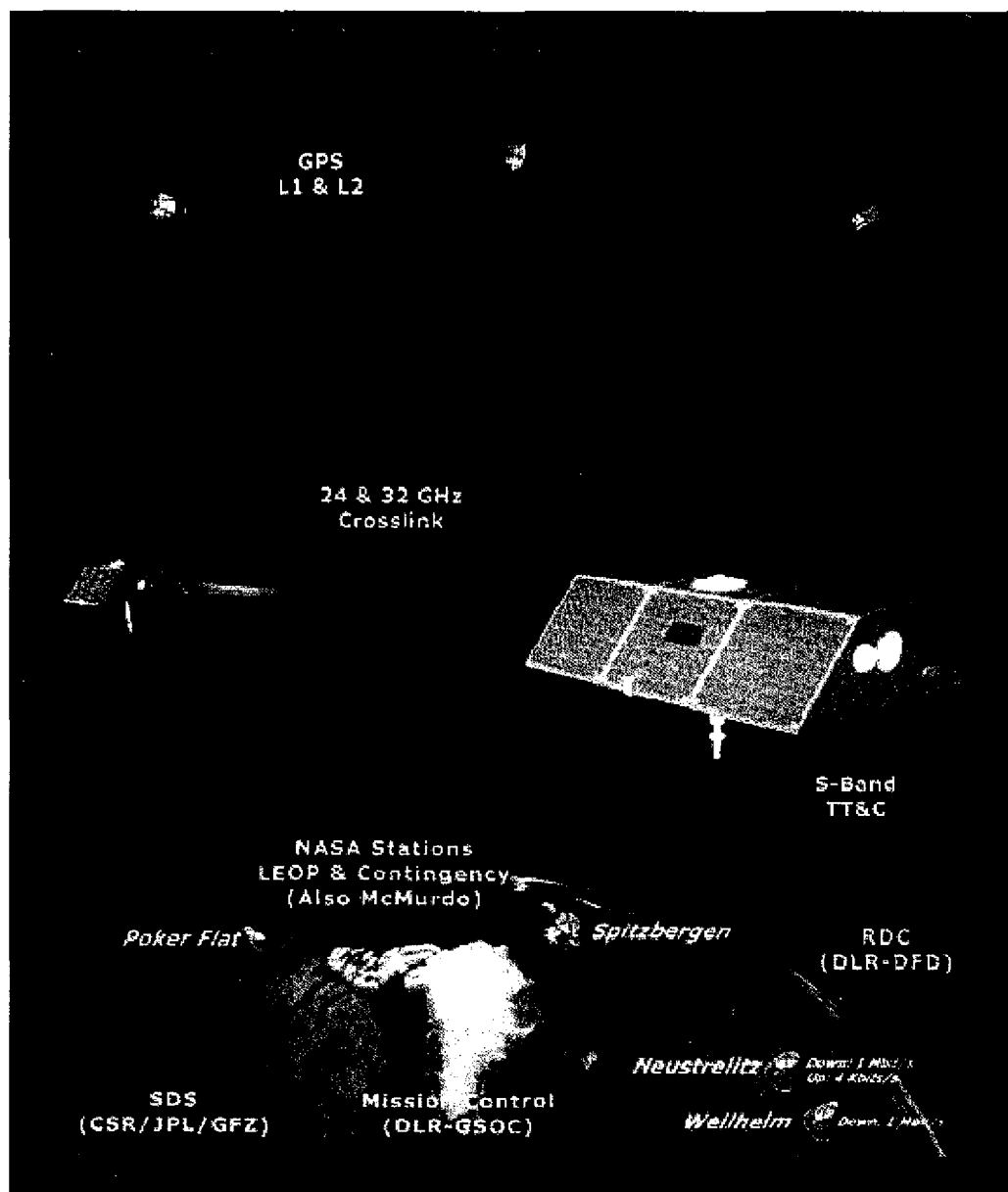
Fig. 10. Illustration of the twin US-German GRACE spacecraft. GPS antennas fore and aft, one on each spacecraft, will capture rising and setting occultations.

8. IMPLICATIONS FOR THE FUTURE

With this groundwork completed, COSMIC will inaugurate the age of operational GPS sounding for weather forecasting, climate prediction, ionospheric monitoring, and a suite of
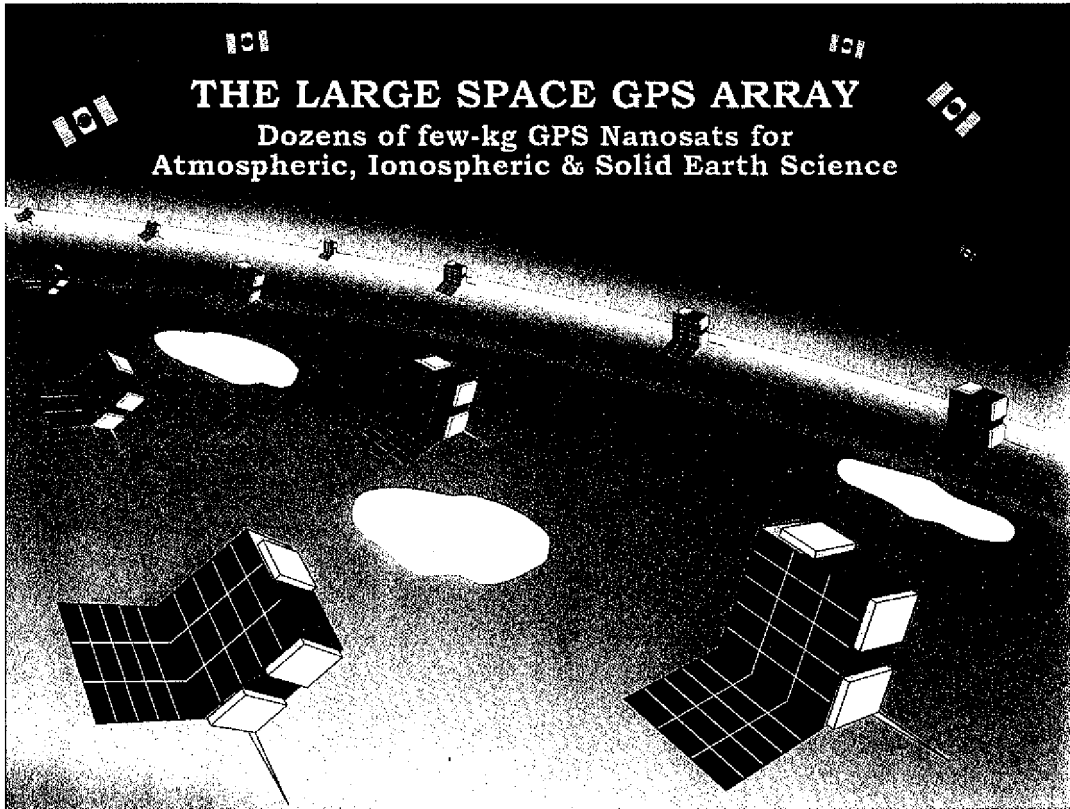
THE LARGE SPACE GPS ARRAY
Dozens of few-kg GPS Nanosats for
Atmospheric, Ionospheric & Solid Earth Science

Fig. 11. Conceptual illustration of proposed array of few-kilogram "nanosats" dedicated to continuous monitoring of the global atmosphere by GPS occultation.

related earth science pursuits. All that went before will be prologue, and COSMIC will become Chapter 1 of, we expect, a long and rewarding adventure. In recent years, much speculation has centered on the likely course of the story to follow, and it must be said that key elements of its development are unclear. In one view, the COSMIC model will be taken to its logical extreme: flight systems will be further miniaturized and we will see dedicated constellations of dozens or even hundreds of tiny free-flyers, each with a mass of a few kilograms, consuming less than 10 watts, and costing a few hundred thousand dollars each when produced in volume (Fig. 11).

There is much to be said for this view. Consider that the next-generation of NASA's occultation receiver—palm-sized, with a mass of a few hundred grams, consuming a few watts—will provide:

• Real time onboard position, velocity, and timing
• Real time onboard attitude and attitude rate determination

- All onboard spacecraft computation and control
- All onboard data storage
- All uplink extraction and command interpretation
- All tracking data for centimeter-level precise orbit determination
- Acquisition of all occultations and ocean reflections

Equipped with a tiny cell-phone chip, each unit will simply dial a local number and send its data through one of the orbiting telecom systems directly to a computer which, within minutes, will generate and distribute finished retrievals. No special ground systems are needed either for tracking or data downlink, and operations crews would be all but non-existent. Very little is needed to convert these tiny components into a finished autonomous spacecraft: an enclosure, solar cells and batteries, magnetic torque rods for attitude control, and (optionally) micropropulsion for crude orbit maintenance. These "nanosats" could be launched in large numbers at little cost as secondary payloads on other launches.

Another view, depicted in our introduction, holds that these same virtues will make the occultation instrument irresistible as an add-on to constellations already planned. The miniature receiver/processor can assume the functions of several discrete spacecraft subsystems, lowering mass, power, and cost in a cascade of economies, while providing a valuable new science dimension and a potentially lucrative data stream. The incremental cost of adding an occultation component to otherwise unrelated constellations could be near zero—or, indeed, negative. And rather than requiring even a cell-phone chip, these space systems, as their principal mission, will provide the global telecom themselves.

On balance we believe that, at least for the immediate post-COSMIC era, the latter scenario is the more likely. The investment needed to realize the "nanosat" concept is not trivial and science agencies tend to proceed with caution. The US Integrated Program Office, for example, which is developing the next generation operational low-orbiting weather satellites (NPOESS), has set itself the modest goal of deploying two operational GPS sensors, matched by a third from Europe, by the year 2008. Another US science official has said that a three-sensor array is sufficient for their research purposes and ten "luxurious." The vision of great constellations deployed at their own expense and risk, even if ultimately economical, is not one that rests easily in their thoughts. That vision has instead been taken up by industry, which has already deployed the first of the great commercial constellations, and, less aggressively, by the military. (The US Defense Department is now evaluating the inclusion of occultation sensors on a future 24-satellite early warning system known as SBIRS-Low.) Together these constellations will comprise hundreds of spacecraft wonderfully suited to the occultation task. Ultimately their own self-interest, if not a love of science, may lead them to add occultation sensing to their mission plans. But that will not happen until the full possibilities and rewards are made manifest through the work we have begun. Until that work is done we can not be certain it will happen at all. For the moment, COSMIC holds the key.

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