IONOSPHERIC MONITORING USING IGS DATA

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Though neither GPS nor IGS are designed to contribute to ionospheric research, IGS provides valuable data sets of GPS observations for ionospheric monitoring. GPS users are mainly interested in the disturbing effects of ionospheric irregularities such as scintillations, for example. They can be analysed with the help of dual-frequency GPS phase observations. The interpretation of the Kokee data for 1992 gives a detailed picture of the scintillation occurrence in the region of Hawaii.

INTRODUCTION

The satellites of the Global Positioning System (GPS) are often considered as "satellites of opportunity" for ionospheric investigations [1]. GPS was not designed for ionospheric research. Nevertheless, the dual-frequency signals offer an excellent means of monitoring ionospheric disturbances and determining the total electron content (TEC) of the ionosphere. The main objectives of the International GPS Geodynamics Service (IGS) are orbit determination and earth rotation monitoring. But the vast amount of continuous dual-frequency GPS tracking data presents a valuable resource for ionospheric research. IGS offers the opportunity to investigate the ionosphere with GPS and without the need to run a GPS network dedicated exclusively to ionospheric research.

IONOSPHERIC EFFECTS ON GPS AND THEIR MONITORING BY IGS

It is widely believed that ionospheric corrections from dual-frequency GPS observations solve all GPS user problems which are due to ionospheric refraction. But this is only true for an undisturbed ionosphere in the mid-latitudes. The worst ionospheric effects are caused by equatorial scintillations which can prevent the tracking of the GPS satellite signals. Both equatorial and polar scintillations are known to cause cycle slips and to complicate their determination. Strong horizontal gradients in the electron distribution can make ambiguity resolution impracticable even for baselines

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as short as 10 km. The world-wide continuous dual-frequency GPS observations of IGS offer an excellent resource to monitor these ionospheric effects. The TEC can be determined from dual-frequency GPS observations. IGS can contribute to the global mapping of the TEC and provide TEC models for the correction of single-frequency measurements of, for example, GPS, VLBI and altimeters.

Equatorial Scintillations

Ionospheric scintillations are caused by small scale irregularities in the electron content of the ionosphere with wavelengths from a few meters to a few kilometers. These electron density irregularities can produce both diffraction and refraction effects. Scintillation or fluctuation in received signal level are variations of amplitude and phase.

The region of equatorial scintillations extends from $\pm$ 30° either side of the earth's magnetic equator. The strongest effects are found at approximately $\pm$ 10°. Scintillations take place between sunset and midnight with activity on occasion continuing until dawn. There is a seasonal dependence: in the American, African and Indian longitude regions, effects are strongest between September and March, but from April through August chances are small of having significant scintillations. In the Pacific region, however, the situation is reversed [2]. Furthermore, scintillation effects depend on the 11-year solar cycle. Their occurrence increases with an increase in the solar sunspot numbers. From 1989 to 1993, they are especially strong due to the maximum of solar cycle No. 22. After 1994, minimal occurrence and minimal strength can be expected for about 5 years. But around the year 2000, scintillation effects will increase again.

The severest effects of small scale irregularities are signal fading and signal enhancement, called amplitude scintillations. The signal level can drop below the receiver's lock threshold. This threshold depends on the bandwidth of the GPS receiver system and on the type of tracking channel. A code-correlation channel can stand lower signal levels than a squaring channel or a cross-correlation channel. Squaring the received signal results in a low S/N (Signal to Noise Ratio), roughly 30 dB lower than that obtained by code-correlation. The data loss and the number of cycle slips due to amplitude scintillations are larger for squaring channels than for code-correlation channels. The data loss can reach up to 100% during scintillation occurrence [3]. Cross-correlating the L_1 and L_2 signals in order to obtain the ionospheric group delay also results in a low S/N. An increased data loss and an increased number of cycle slips are expected. However, detailed studies on the effects of equatorial scintillations on cross-correlation channels are still lacking.

Amplitude scintillations can be monitored by the interpretation of S/N time series provided by geodetic GPS receivers for each observable. Rapidly changing values indicate scintillation activity. S/N are stored in the raw data. Unfortunately, the Receiver INdependent EXchange format (RINEX) contains the signal strength only projected onto the interval 1-9, i.e. most of the information gets lost. Since IGS works with the RINEX format, IGS data are not appropriate for the detection of amplitude scintillations.

Phase scintillations are a result of sudden changes in ionospheric refraction or of diffraction effects. They can reach up to some cycles of L_1- or L_2-signals between two epochs with a common epoch rate of 10, 20 or more seconds. They complicate cycle slip detection and determination. These refractive effects can cause GPS receiver systems to lose lock due to the rapid frequency changes in the received signal. The apparent range-rate errors can produce a Doppler shift change of greater than 1 Hz per second, which is more than the bandwidth of many receivers. Usually, ionospheric refraction causes the $L_1 - L_2$ phase difference to change slowly. In the case of phase scintillation however, the phase differences can change rapidly by more than 0.5 cycles of L_2 so that L_2-channels which are aided by L_1 tracking data lose lock.

Phase scintillations can easily be detected in single-station dual-frequency phase data. Even with a low data rate of 1 min they can be identified, localized and their strength can be estimated. Hence, IGS can contribute to climatological studies of phase scintillation occurrence.

Polar Scintillations

Polar scintillations are not as strong as those near the equator. Their occurrence is closely related to magnetic storm activity. Phase and amplitude scintillations have been observed with GPS signals, but no code tracking problems have been reported. However, users relying on continuous carrier phase data are seriously affected by scintillation activity, because of an increased number of cycle slips and difficulties in their determination [4,5].

The strongest ionospheric activity does not take place in the polar cap regions but rather in the auroral zones situated between magnetic latitudes of about 64° and about 70°. During very strong magnetic storms, these auroral effects can extend well into the mid-latitudes.

The equatorward extension of polar scintillation activity is of primary interest to GPS users in the mid-latitudes. IGS can provide information on scintillation occurrence, scintillation intensity and the equatorward boundary of ionospheric activity. Thereby it can contribute to the understanding of the dependence of L-band scintillations on magnetic activity and to reliable scintillation activity prediction.

Travelling Ionospheric Disturbances

Travelling Ionospheric Disturbances (TIDs) are wavelike structures which may imply variations in the ionospheric electron density of several percent of the total electron content. Large-scale TIDs (LSTIDs) have horizontal phase speeds of 300 - 1000 m/s, periods ranging from 30 min - 3 h and horizontal wavelength exceeding 1000 km. They propagate equatorward from the polar regions, where they are supposed to be generated in the auroral zones. Medium-scale TIDs (MSTIDs) have horizontal phase speeds of 100 – 300 m/s, periods from 12 min to about 1 hour and horizontal wavelengths of several hundred of km. They occur much more frequently than LSTIDs, and their origin is not known, although many possible excitation mechanisms have been proposed [6].

Gradients in the electron density attributed to MSTIDs affect the double difference observable. Ionospheric effects of more than half a cycle of L_1 or L_2 were found in double differences of baselines even shorter than 10 km. Algorithms for rapid-static or on-the-fly ambiguity resolution can fail in the presence of MSTIDs. Single-frequency relative positioning can experience coordinate errors of 15 ppm and more [7].

MSTIDs can be detected in time series of single-station dual-frequency phase data. IGS can contribute to climatological studies of TIDs.

Large Scale Horizontal Gradients

In the case of relative positioning with GPS, not the Total Electron Content (TEC) but horizontal gradients of TEC are the determining factor. The largest horizontal gradients in the electron density are found in the regions of the equatorial anomalies ($\pm$ 10–20° magnetic latitude). On the one hand there are large gradients from the equatorial crest to the mid-latitudes and in the opposite direction to the magnetic equator (north-south gradients). On the other hand, minor gradients are caused by the diurnal cycle of the ionospheric electron content (east-west gradients). In the region of the southern equatorial anomaly in South America, horizontal gradients observed with GPS were as large as $30 \cdot 10^{16}\ el/m^2$ per 100 km in north-south [3]. This value is equivalent to an ionospheric effect on single differences between stations of a 10 km baseline of up to several cycles of L_1 or L_2 or up to about 1 cycle of the widelane linear combination. The resolution of double difference ambiguities is impossible under these conditions with standard algorithms or single-frequency data.

A modelling of these gradients can only be successful in regional networks. However, IGS can contribute to the localization of the equatorial anomalies and to studies on their temporal variations.

Total Electron Content

The Total Electron Content (TEC) can be determined from dual-frequency code or carrier-phase measurements. However, the codes transmitted from GPS satellites at the two frequencies show a synchronization bias due to different hardware paths inside the transmitter. Similar effects are also known for the receiver hardware. The phases experience biases due to the unknown carrier phase ambiguities and due to differential equipment phase delays. An estimation of the combined satellite and receiver differential delays (and ambiguities) can be performed from GPS observations [8,9]. In areas and time periods of very small horizontal gradients (mid-latitude, night-time) the achievable accuracy is about $2 \cdot 10^{16}\ el/m^2$. But in areas and time periods of large gradients (e.g. equatorial anomaly), the accuracy deteriorates considerably

[10]. Then predetermined satellite differential group delays and internally calibrated receivers give better results.

IGS can contribute to the global mapping of the TEC and the observation of long term changes in TEC. Correction values for single-frequency GPS positioning, single-frequency VLBI or single-frequency altimeter measurements can be provided in the form of global models [11,12]. More precise regional models can only be produced for regions of a dense network of IGS stations (e.g. in Europe).

DETECTION OF SCINTILLATIONS

Severe effects on GPS measurements are caused by equatorial scintillations. Amplitude scintillations, being the main cause of data loss, can be detected in the measured S/N. However, the RINEX format does not provide this information in a usable form. Phase scintillations can easily be detected in the "geometry-free" linear combination of single-station dual-frequency phase measurements. In order to eliminate the unknown carrier-phase ambiguities, differences between epochs (Rate of Total Electron Content - RoT) are formed [10]:

$$RoT(t_j, \Delta t_{ij}) = S \cdot \Big((\phi_1(t_j) - \phi_1(t_i)) \cdot \lambda_1 - (\phi_2(t_j) - \phi_2(t_i)) \cdot \lambda_2 \Big) \tag{1}$$

with

$$\Delta t_{ij} = t_j - t_i = 1 \quad [min] \tag{2}$$

and

$$S = \frac{1}{40.3} \cdot \frac{f_1^2 \cdot f_2^2}{f_1^2 - f_2^2} = 9.52 \cdot 10^{16} \quad [el/m^3]. \tag{3}$$

Subscripts 1 and 2 identify the signals L_1 and L_2, t_i and t_j are the measurement epochs, ϕ [cycles] are the measured carrier phases, λ [m] the carrier wavelengths and f [Hz] the GPS frequencies. S converts the differences of dual-frequency phase measurements from [m] to $[el/m^2]$. Often the unit $TECU$ is used: $1\ TECU = 10^{16}\ el/m^2$. All frequency independent errors are removed by forming the "geometry-free" linear combination. Significant remaining errors are multipath, which can reach up to 0.3 $TECU/min$, and the random observation errors, which usually do not exceed 0.07 $TECU/min$. Cycle slips have to be detected in the pre-processing. They do not need to be estimated.

RoT time series contain the complete ionospheric information of dual-frequency phase data. They are especially suitable for the detection of ionospheric disturbances (scintillations, TIDs), but they also show the absolute electron content and large-scale horizontal gradients. A smooth and increasing RoT curve indicates an undisturbed satellite path. Phase scintillations appear as jumps due to sudden changes in ionospheric refraction. A phase scintillation index I_{RoT} can be computed from RoT. In a first processing step the low frequent changes of RoT are removed. They are a result of the absolute electron content and of large-scale horizontal gradients. The index is computed as RMS over the remaining parts of the RoT time series:

$$I_{RoT} = 10 \cdot \mathrm{RMS}\left(\overline{RoT}_{\Delta t=1\ min}\right) \qquad (4)$$

In order to separate TIDs from scintillations, the frequency spectra of RoT time series are analysed. Periods of 10 to 30 min indicate the occurrence of MSTIDs. Disturbances of higher frequencies are considered to be scintillations. If scintillations are only to be detected but not to be classified by their strength, the zenith angle dependence of the index is negligible.

EXAMPLE: KOKEE, HAWAII 1992

Hawaii is located at 20°N magnetic latitude. It belongs to the ionospheric equatorial region. Though the main scintillation activity takes place around ±10° magnetic latitude, Hawaii is also expected to be affected. Moreover, large-scale gradients at the northern boundary of the northern equatorial anomaly are believed to affect GPS data from Kokee.

Kokee data for 1992 are available for more than the three months of the IGS test campaign. With the exception of a data gap from mid-September to mid-November, one GPS receiver was continuously working. Average months show data loss of 10% to 30% due to receiver failures and other causes (Table 1).

RoT plots provide pictures of the ionospheric conditions (Fig.1). Large-scale horizontal gradients were strong from January to March and in November and December. Disturbances of periods of 10 to 30 minutes were detected a couple of times during day-time hours. No scintillation occurrence was detected from January to April and in November and December (exception: December 16). The observed scintillation activity from March to September/October was not as severe as scintillation activity monitored closer to the magnetic equator [3]. No significant data loss could be justified with scintillation activity. Detailed pictures of percentage occurrence of phase scintillations were produced with the help of I_{RoT} for 15-min blocks of data. The coordinates of the intersection points of the satellite signals with a single-layer ionosphere model at a height of 400 km (ionospheric points) were attributed to each

Month	1992	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Data Rate	[sec]	120	120	120	120	120/30	30	30	30	30	–	30	30
Available Data	[%]	80	81	90	83	90	67	93	68	33	0	49	21

Table 1: Available Kokee data for 1992.

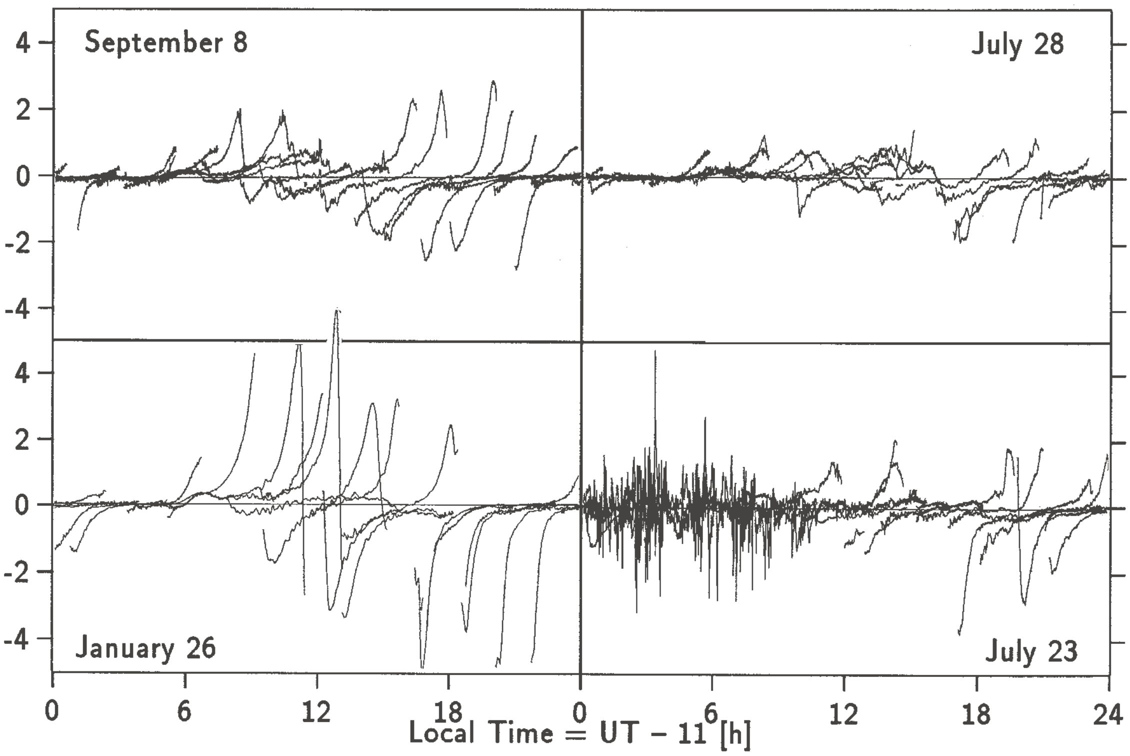

Figure 1: RoT plots of all satellites and of 24-hour data sets provide a survey of the ionosphere. The figure shows examples from Kokee in 1992. RoT units are [TECU/min], elevation mask 10°, *local time of observation site.*

September 8*: average ionospheric conditions, no disturbances, the effects of large-scale horizontal gradients dominate over the effects of a high TEC, large-scale horizontal gradients in the electron content occur because of a low electron content north of the station (mid-latitude) and a high electron content in the south (equatorial anomaly), satellites travelling south-north cause large negative RoT-values with their rising, satellites travelling north-south cause large positive RoT-values with their setting, in contrast to mid-latitude sites there is no single diurnal maximum of the electron content but rather two maxima around local noon and in the early night, the large-scale gradients of the second maximum usually exceed the gradients of the first maximum.*

July 28*: low electron content and only little effects of gradients, no significant disturbances, second maximum recognizable.*

January 26*: very strong large-scale horizontal gradients in the electron content, gradient effects of this strength were common from January to March and in November and in December of 1992.*

July 23*: night-time equatorial scintillations of medium strength (as compared to scintillations observed in South Brazil in 1992 [3]),* $I_{RoT} = 3...11$, *no data loss due to scintillation activity.*

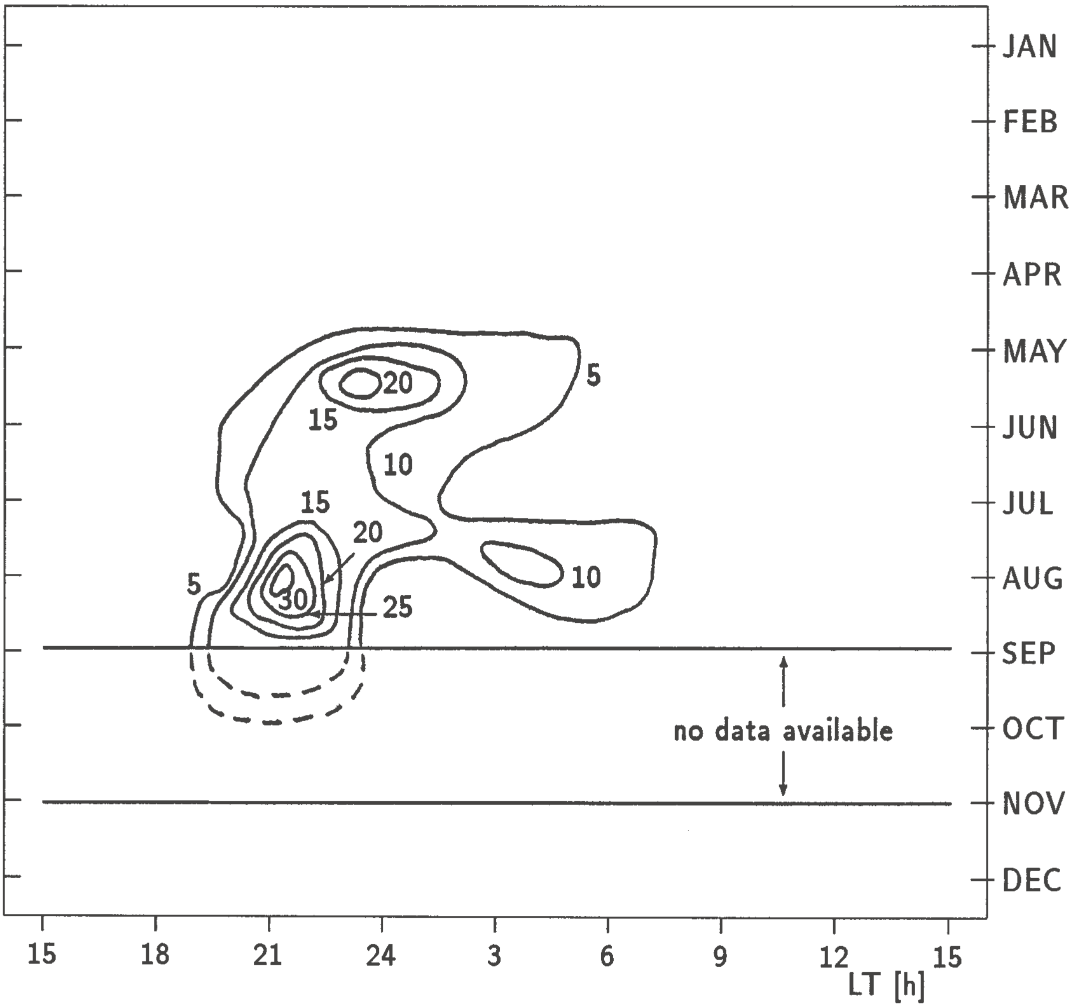

Figure 2: Percentage occurrence of phase scintillations with $I_{RoT} \geq 3$ in periods of 30 minutes, elevation mask 15°*, mid-month marked, local time of ionospheric points (400 km).*

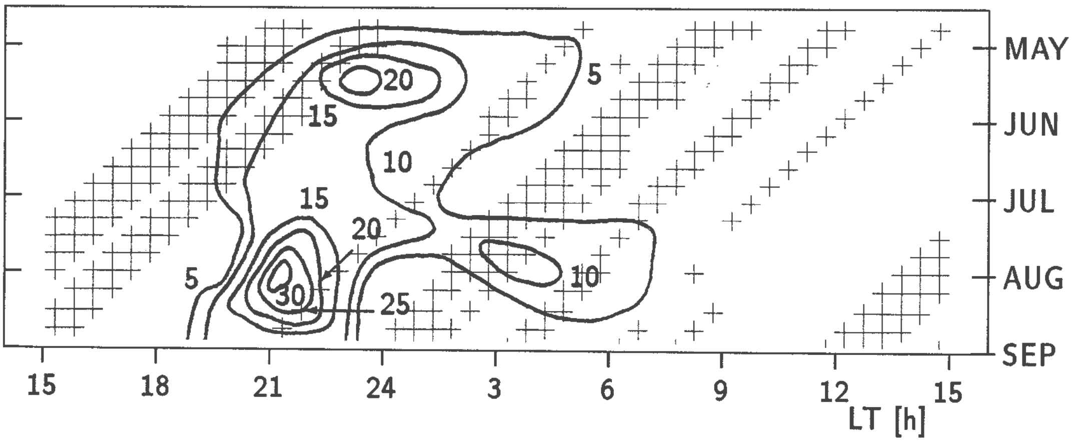

Figure 3: Part of Figure 2 superimposed on a map which shows periods of 30 minutes without any GPS observations south of 18°*N latitude of ionospheric points (400 km).*

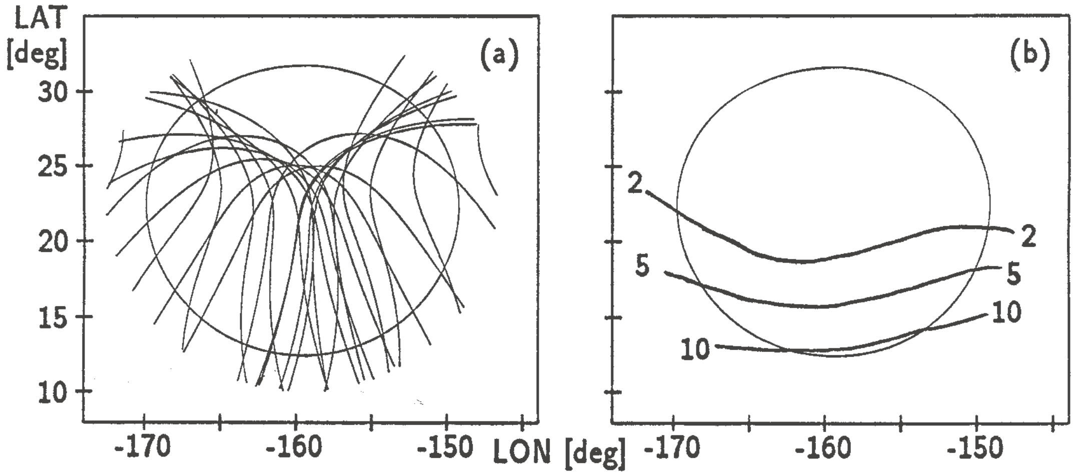

Figure 4: (a) Ionospheric points (400 km) of the satellite orbits for Kokee, September 1992, "circle" shows 15° *deg elevation mask. (b) Percentage occurrence of night-time phase scintillations with* $I_{RoT} \geq 3$ *during May and mid-September, 20 h and 6 h LT, ionospheric points (400 km), "circle" shows* 15° *deg elevation mask.*

index value. Hence, GPS ionospheric observations cover an area with a radius of more than 1000 km (Fig.4a). The figures reveal that the main activity was limited from sunset to local midnight, but on occasion continuing until dawn (Fig.2). Latitudinal and longitudinal distribution of scintillation activity shows a decrease in scintillation activity with an increase in latitude. North of Kokee hardly any scintillation activity took place (Fig.4b). Though only 12% of the observations were collected south of 18°N latitude of the ionospheric points, more than 50% of the detected scintillations occurred in this region. The incomplete coverage of GPS satellite passes south of 18°N causes periods of up to some hours without any data in this region (Fig.3). This incompleteness explains some features of the scintillation occurrence map such as the late beginning of scintillation activity at approximately 21 h LT in May and the activity hole after midnight in August/September.

In 1993, decreased scintillation activity can be expected due to the decrease in sun activity. Otherwise similar ionospheric conditions can be predicted. At the beginning and at the end of the year, the ambiguity resolution of GPS baseline measurements will be affected by large-scale gradients. From May through September/October equatorial night-time scintillations will occur. With the possible introduction of Anti-Spoofing (A-S) and thereby the necessity to track the L_2-signal with squaring or cross-correlation channels, data loss due to scintillations will increase.

CONCLUSION

The vast amount of continuous dual-frequency GPS data gathered by IGS provides a valuable resource for ionospheric research. Users of the GPS positioning service are mainly interested in the disturbing effects of ionospheric irregularities such as scintillations. A phase scintillation index can be computed from single-station dual-frequency GPS phase observations. Statistical analyses of scintillation activity can be performed with its help.

The interpretation of the Kokee data for 1992 shows that Hawaii lay at the northern boundary of scintillation activity in 1992 and that the occurrence of these disturbances were limited to the month of May to September/October and to a period of approximately 19 h to 6 h local time. The example demonstrates the usefulness of ionospheric monitoring using permanent tracking data for the planning of GPS campaigns.

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